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Waterways Experiment Station

Water-Level Analysis for Cumberland Sound, Georgia

by *Nicholas C. Kraus, WES*
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WES

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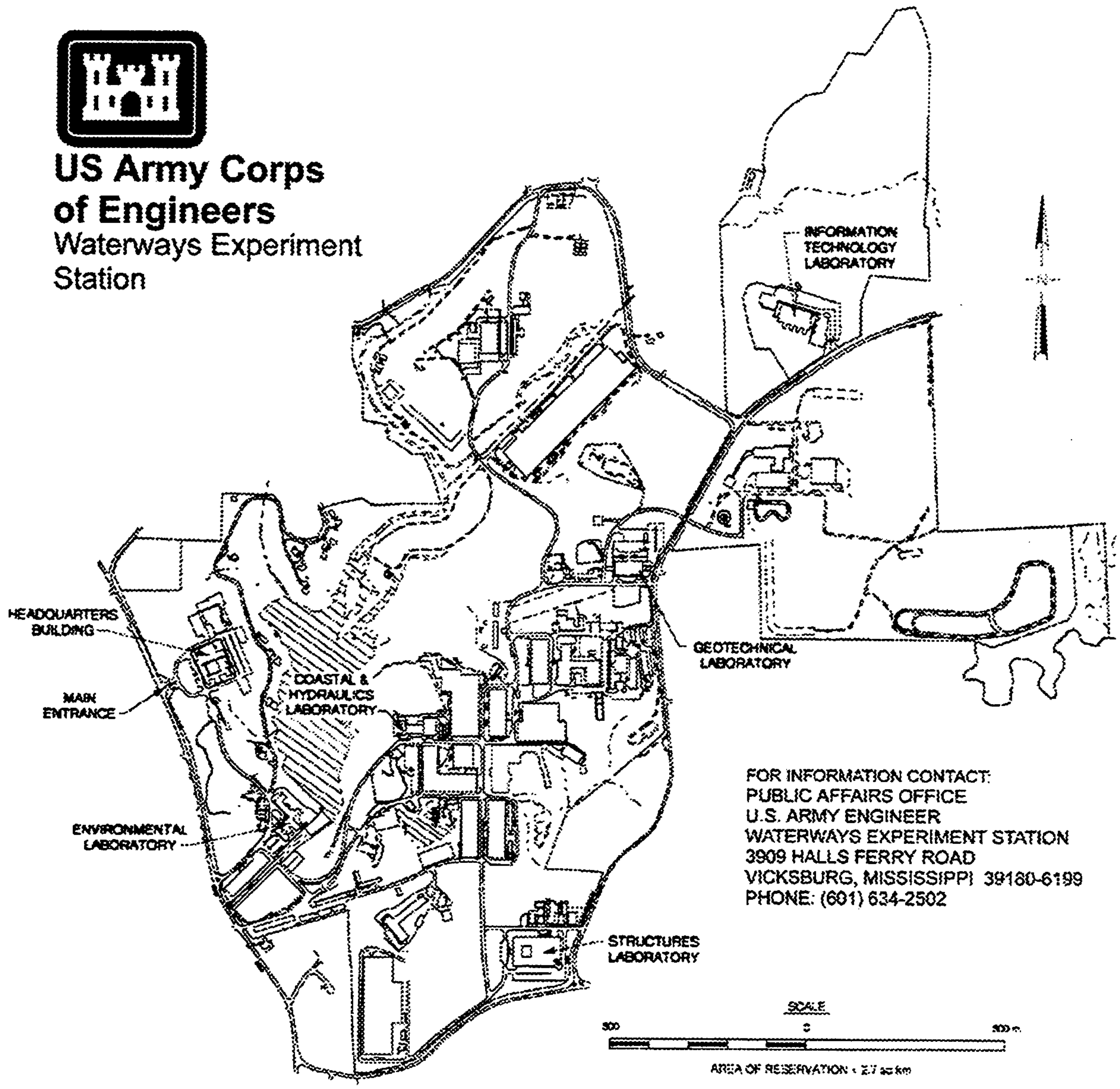

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Preface

This study was conducted and the report prepared from 1 August through 30 December 1993, by staff of the Conrad Blucher Institute for Surveying and Science, Texas A&M University-Corpus Christi, TX, under contract with the U.S. Army Engineer Waterways Experiment Station (WES), in Vicksburg, MS. The authors are Dr. Nicholas C. Kraus, former Director and Professor at the Blucher Institute, and currently affiliated with the WES Coastal and Hydraulics Laboratory (CHL), as well as Dr. R. Christian Faucette and Ms. Mary K. Rogan of the Blucher Institute. The contract was administered at WES by Mr. H. Lee Butler, Chief, Research Division, CHL. Mr. Butler provided technical review. Dr. James R. Houston is the Director of CHL and Messrs. Richard A. Sager and Charles C. Calhoun, Jr., are Assistant Directors.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet per second	0.02831685	cubic meters per second
cubic yards	0.7645549	cubic meters
degrees	0.01745329	radians
feet	0.3048	meters
gallons	3.79	liters
square miles	0.003860937	hectare

1 Introduction

Study Background

Cumberland Sound, Georgia, is a large and complex estuary some 240-sq-miles[1] in area (Fisakerly, Fagerburg, and Knowles 1991) connected to the Atlantic Ocean through a dredged inlet channel called St. Marys Entrance (Figure 1). Cumberland Sound receives fresh water and runoff from St. Marys River, Crooked River, and numerous streams and creeks. McAnally, Letter, and Fagerburg (1993) found that St. Marys River has a long-term average freshwater discharge into the sound of 1,500 cfs, and Crooked River follows with 100 cfs. In addition, at least two paper mills pump deep-well groundwater effluent into Cumberland Sound in amounts on the order of 150 million gallons per day.

St. Marys Entrance consists of a Federally maintained navigation channel protected by two jetties separating Cumberland Island, Georgia, to the north and Amelia Island, Florida, to the south. The U.S. Navy (USN) operates the Kings Bay Submarine Base that is located in the state of Georgia on an inner arm of Cumberland Sound, and commercial and recreational boats bound to or from Fernandina Beach, Florida, as well as military vessels, pass through St. Marys Entrance. The channel through St. Marys Entrance is now maintained at a 50-ft depth (mean low water (mlw)) through dredging that occurred from 1986-1988. The mean tidal range in Cumberland Sound is about 5.8 ft.

The channel at St. Marys Entrance has been dredged since at least 1903, at first for commercial navigation interests. Major dredging with channel enlargement occurred in the 1950s, mid 1970s, and in the mid- to late 1980s for military interests. From 1986-1988, USN-sponsored dredging of the St. Marys navigation channel running through the Entrance and into Cumberland Sound removed an estimated 9,639,700 cu m of sediments that were either placed on or in the nearshore of Amelia Island or in disposal sites offshore. A summary of this dredging, termed "new work" to signify removal of original sediments, is given in Table 1, compiled from information given by Smith et al. (1994). In Table 1, the term "Event" denotes the dredging project or event number as

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page vii.

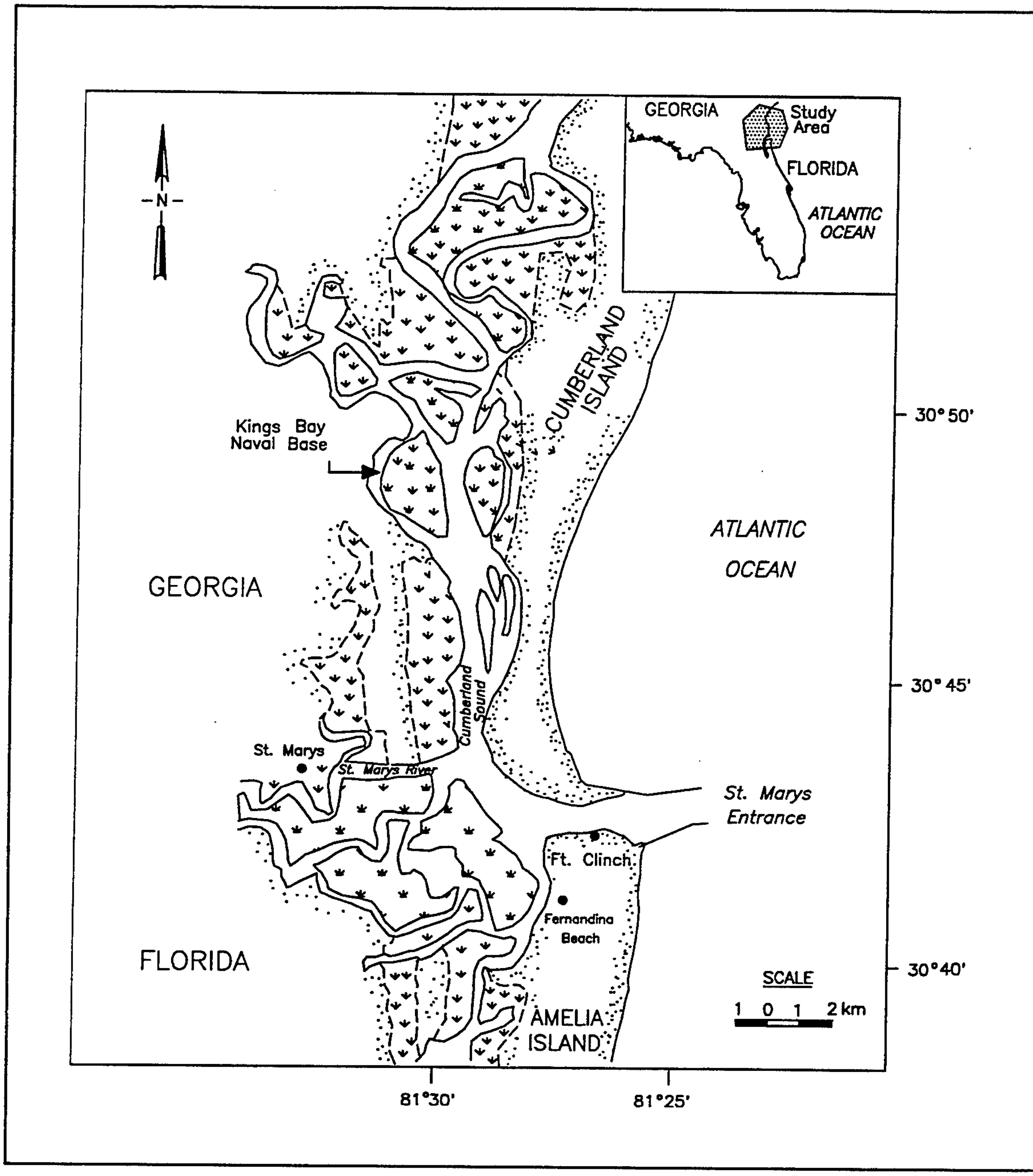

Figure 1. Location map for Cumberland Sound, Georgia (from Pope and Richardson (1994))

identified by Smith et al. (1994). Table 2 lists all maintenance dredged volume for the subject time period, which is the volume of material removed that had been transported into the vicinity of the channel by water currents or wind.

The significant dredging that occurred from 1986-1988 raised the question of whether the water level in Cumberland Sound had been altered as a result. If, for example, the water level would rise with respect to the adjacent land, portions of the extensive wetland in Cumberland Sound might be inundated and lost. The

Table 1
Dredging History[1] of New Work[2] at St. Marys Entrance Channel and Cumberland Sound Channel from Station 0+00 to 220+00

Event No.	Year	Location	Amount of Dredged Material cu yd	Amount of Dredged Material cu m
St. Marys Entrance Channel 1987-1988				
33	1987-88	Entrance Channel - New Work	906,800	693,300
34	1987-88	Entrance Channel - New Work	1,618,200	1,237,200
35	1988	Entrance Channel - New Work	5,456,000	4,171,400
36	1988	Entrance Channel - New Work	530,000	405,200
Total New Work Dredging, St. Marys Entrance Channel			8,511,000	6,507,100
Cumberland Sound Channel 1986-1988				
7	1986	Sta 172+50 to 200+00 - New Work	977,600	747,400
8	1986	Sta 152+50 to 172+50 - New Work	346,600	265,000
9	1987	Sta 145+00 to 155+00 - New Work	228,300	174,600
10	1987	Sta 140+00 to 145+00 - New Work	151,000	115,400
11	1987	Sta 130+00 to 140+00 - New Work	258,200	197,400
12	1987	Sta 120+00 to 130+00 - New Work	309,400	236,600
13	1988	Sta 95+00 to 105+00 - New Work	232,200	177,500
14	1988	Sta 90+00 to 95+00 - New Work	117,500	89,800
15	1988	Sta 115+00 to 120+00 - New Work	146,200	111,800
16	1988	Sta 105+00 to 115 - New Work	261,000	199,600
17	1988	Sta 80+00 to 90+00 - New Work	227,300	173,800
18	1988	Sta 65+00 to 80+00 - New Work	305,000	233,200
19	1988	Sta 0+00 to 40+00 - New Work	267,500	204,500
20	1988	Sta 40+00 to 65+00 - New Work	269,400	206,000
Total New Work Dredging, Cumberland Sound Channel			4,097,200	3,132,600
Total New Work Dredging St. Marys Entrance & Cumberland Sound			12,608,200	9,639,700

[1] Taken from Kraus and Gorman (1994), Tables C2 and C3.
[2] New work indicates deepening of channel to new depths.

present study was commissioned by the U.S. Army Engineer Waterways Experiment Station (WES) to review and interpret the water-level record available from a tide station operated by the National Ocean Service (NOS),

Table 2
Dredging History[1] of Maintenance Work[2] at St. Marys Entrance Channel and Cumberland Sound Channel from Station 0+00 to 220+00

Event No.	Year	Location	Amount of Dredged Material	
			cu yd	cu m
St. Marys Entrance Channel 1986-1988				
32	1987-88	Entrance Channel - Maintenance	321,000	245,500
37	1988	Cut 1N - Sta 240+00 to 320+00 - Maintenance	720,000	550,500
Total Maintenance Dredging, St. Marys Entrance Channel			1,041,000	796,000
Cumberland Sound Channel 1986-1988				
None	1986-88	N/A - Maintenance	0	0
Total Maintenance Dredging, St. Marys Entrance & Cumberland Sound			1,041,000	796,000

[1] Taken from Kraus and Gorman (1994), Tables C2 and C3.
[2] Maintenance indicates dredging to maintain the channel at a given depth.

National Oceanic and Atmospheric Administration, that is located at Fernandina Beach, Florida, in Cumberland Sound.

Extensive studies of the physical processes and ecology in and around Cumberland Sound have been conducted on behalf of the USN. In support of expansion of the submarine base at Kings Bay to accommodate Trident submarines, in the 1980s the Navy initiated studies of the physical processes (e.g., Vemulakonda and Scheffner 1987, 1988, Granat et al. 1989, Granat and Brogden 1990, McAnally and Granat 1990) and ecology of the site (e.g., Cofer-Shabica 1991). Most of the coastal physical process studies were conducted for the USN by the WES Coastal and Hydraulics Laboratory, and this work is presented in a comprehensive two-volume technical report (Kraus, Gorman, and Pope 1994, 1995) which contains numerous citations to the related literature. Most of the estuarine physical process studies were conducted by the WES Coastal and Hydraulics Laboratory, which performed both field data collection and analysis, and numerical and physical modeling (e.g., Granat et al. 1989; Granat 1990; Granat and Brogden 1990; Fagerburg, Coleman, and Parman 1991a, 1991b).

Objectives of Study and Approach

Objectives of this study are to determine if recent (1986-1988) dredging along Cumberland Sound and St. Marys Entrance has altered the water level in Cumberland Sound and to quantify the change if it is found. This work follows a major coastal processes study performed by WES as documented in Kraus,

Gorman, and Pope (1994, 1995) and was conducted separately at the final stages of that study to allow the longest possible tide record to be analyzed within the study schedule. This report provides information on Cumberland Sound water levels up to December 1992.

The approach is to perform an extensive analysis of the water-level record available from the NOS Fernandina Beach tide station. This record is also compared to those at the closest long-term NOS tidal stations to the north (Fort Pulsaki (Savannah), Georgia) and to the south (Mayport, Florida). Basic comparisons are made by visual examination of trends in water level and tidal range and calculation of trends. A statistical test is also employed to compare changes in water level before and after dredging.

An introduction, background on the study site, and objectives of the study are given in Chapter 1. Chapter 2 gives an introduction to water-level analysis measurement equipment and procedures. Chapter 3 contains the main technical content of this report and results of the water-level analysis. Conclusions of the study are presented in Chapter 4. Additional material on statistical tests of water level change is contained in Appendices A and B.

2 Introduction to Water-Level Measurement and Analysis

The water level in oceans and lakes moves up and down in both periodic and non-periodic motions on many time scales. Short-term water-level change contains three types of contributions:

a. A deterministic contribution given by the astronomic tide.

b. A random contribution given by a variety of processes including meteorologic forcing (changes in wind, air pressure, precipitation, sunshine, etc.) and arrival of short- and long-period surface-gravity waves.

c. An episodic contribution as through quasi-periodic climatic changes and storms, and through human activities, such as altering of the coastal configuration and bathymetry.

Coastal morphology changes may be natural, such as those caused by tectonic movement and local land or sea-bottom subsidence, or they may be human-induced, such as those caused by dredging of channels and harbors, and by subsidence produced by pumping out of underground water and gas. Hydrodynamic-morphology interactions particular to a site, such as seiching, also affect water level. Factors that determine water level are numerous, and their quantification is difficult. These factors can also be subtle and difficult to quantify, for example, as being related to the amount of water in the ocean. Evaluation of water level depends on location along the coast, time, measurement interval, and time spanned by the measurement interval (tidal epoch) if an average is being considered.

As a wide-area and long-term phenomenon, change in water level is difficult to distinguish from change in land level. Therefore, the term "relative sea-level change" is often used to refer to water-level change that could occur through a combination of change in elevation of the water and of the adjacent land. Engineering implication of water-level change have been discussed by the National Research Council (1987) and the American Society of Civil Engineers Task Committee (1992), the latter article specifically concerned with bays and

estuaries. Emery and Aubrey (1991) give a comprehensive discussion of relative sea-level change including theoretical background, case studies, and practical aspects of measurement.

Tidal Datums

In the United States, NOS is the Federal agency legally responsible for determining water-level datums. Quoting from Hicks (1989), "For marine applications, (a datum is) a base elevation used as a reference from which to reckon heights or depths. It is called a tidal datum when defined in terms of a certain phase of the tide." The NOS uses specific instruments and calculation procedures to measure water-surface elevation and to subsequently compute tidal datums (Marmer 1951, Swanson 1974). A review of definitions and procedures for determining water level pertinent to this study is given in this chapter. A description of the tide station at Fernandina Beach, Florida, hereafter abbreviated to "Fernandina," is also given.

Tidal datums are elevations computed as means of some measured quantity over the National Tidal Datum Epoch, which is presently the 19-year interval 1960 to 1978. Tidal datums are also computed over shorter time periods, such as a month or year, and referenced as such (inclusion of the time interval covered by the meaning procedure). In the present study, monthly and annual values of mean tide level (mtl) and mean range of tide, abbreviated as Mn by NOS, are analyzed.

The mtl value, also called half-tide level, is a tidal datum and is equal to the arithmetic mean of mean high water (mhw) and mlw, both of which are tidal datums. The value for mhw and mlw are the averages of all the high-water heights and low-water heights, respectively, in the given time interval. High water is the maximum height reached on a rising tide, and low water is the minimum height reached on a falling tide. Mn is not a datum because it is not an elevation, but it is defined in terms of tidal datums as the difference in height between mhw and mlw over a certain time interval.

Given values of mtl and Mn, values of mhw and mlw can be constructed as mhw = mtl + Mn/2 and mlw = mtl - Mn/2. Use of mtl and Mn allows examination of possible changes in the absolute water level and in the range, and takes into account the circumstance that a comprehensive average such as mtl may remain constant while the range through which the tide changes may either increase or decrease. Also, Mn is a relatively stable quantity with properties somewhat different than mtl or other tidal datums.

Studies of water-level change typically consider the tidal datum mean sea level (msl), which is the arithmetic mean of hourly heights observed over the National Tidal Datum Epoch or other specified time interval, such as month or year (Hicks 1989). For a perfectly symmetric tide, msl and mtl will be the same. However, asymmetries in the tide introduce a small difference in these datums which may be positive or negative. In the case of the Fernandina tide station, mtl

lies below msl by about 0.1 ft, and monthly differences in these quantities typically vary between -0.08 and -0.13 ft. The datum mtl was used in this study because of its direct relation to Mn and mhw, which were also of interest. Because of the (empirically fixed) relation between msl and mtl, trends in change will be the same.

Measurement and Analysis of Water Level

Swanson (1974) discusses accuracy in determining tidal datums. Summarizing from that work, the overall accuracy of a tidal datum is dependent upon the accuracies of:

a. The data-collection or measurement system.

b. The level connection between the measurement system and benchmarks.

c. The computational procedures used to determine the datum.

Manuals written by Marmer (1951) and by the predecessor organization to NOS, the Coast and Geodetic Survey, (1965 and reprinted in 1974) describe measurement and analysis procedures to those dates. In the early 1990s, NOS widely introduced the Next Generation Water Level Measurement System (NGWLMS) (Edwing 1991) based on acoustic technology. Previously, water-level measurements had been made by either a float-actuated analog device or an Analog-to-Digital (tide) Recorder (ADR), which also employed a float.

Table 3 lists the years of available tide data from NOS for the three stations examined in this report, together with the type of tide gauge used. For clarity, in this report a "tide station" refers to the location of a water-level measurement instrument installed and maintained to certain standards specified by NOS, and a "tide gauge" refers to the apparatus used to measure water level. NOS frequently uses the terminology "water level" to encompass descriptors "tide" or "tidal" for coastal regions and "lake level" for the Great Lakes.

Water elevations are compiled by NOS from averages of readings taken every 6 min. Occasionally, small or large breaks occur in the data due to equipment malfunction, equipment maintenance, or other reasons. Breaks are filled in by NOS through careful analysis that takes into account the overall record at the station, readings at the station before and after the break, and measurements from neighboring tide stations. Swanson (1974) estimated probable error in using a 12-month series of measurements as opposed to a 19-year series as 0.05 ft for the east coast of the United States. We will assume this value as an upper limit to the error associated with pragmatics of calculation in determining a yearly tidal datum. Swanson (1974) also concluded that leveling error was much smaller than measurement error and calculation error (order of 0.01 ft), and could be neglected.

Table 3
Tide Station Gauge Type by Station and Length of Data Record

Tide Gauge Type	Station (NOS Number)	Years of Data Used
Float actuated (analog strip chart)	Fort Pulaski (8670870)[1]	1935-1965
	Fernandina (8720030)[1]	1897-1965
	Mayport (8720220)[1]	1895-1965
ADR (digital punched tape)	All	1965-1992
NGWLMS[2]	Being phased in	1992-present

[1] Represents station location; actual position of the tide gauge may vary.
[2] NGWLMS not in use at these stations at time of this writing.

No documentation stating accuracy of tide gauges could be found in this study. From discussions with knowledgeable personnel, it is estimated that the potential average error in measurement of water level in a single reading of a float-actuated tide gauge is ±0.05 ft under typical conditions. Filling of breaks where data are lacking as required to calculate a tidal datum introduces an unquantifiable error that is believed to be smaller than associated mechanical errors. Not only is the NGWLMS more accurate, but it is also much more reliable and robust than previous systems, reducing breaks appearing in a water-level record and the necessity for manually filling the data breaks. If the error in water-level measurement is random, then a long-term average (over a month or year), as used in this report, should cancel much of the measurement error. If the error contains a systematic component, computation of a change in water elevation also would greatly reduce the total error.

To reduce the undesirable possibility of including land elevation changes in the water-level record, at least five benchmarks are established in the area of an NOS tide station, and the level of the tide gauge is referenced to these benchmarks. If local subsidence or other vertical movement of the gauge occurs, leveling to the undisturbed benchmarks will reveal this change in elevation. Copies of the original data sheets supplied by NOS for the three studied tide stations were examined, and no unaccountable changes in elevation were noted by NOS or the authors of this report. Therefore, local subsidence as produced by deep-well water pumpout is not believed to be a factor in this study. This benchmark elevation check does not preclude the possibility of wide-area change in elevation of the land.

In this study, a possible difference in water level is being sought between time periods before and after dredging. It is therefore relevant to estimate error in the measurement and calculation procedures. Based on the discussion above, the probable maximum error in water level obtained in annual averages is estimated as ±0.05 ft for mechanical tide gauges for the time period encompassing the major analysis period (before 1992). If a water-level difference less than this amount is found, it must be considered as within the range of uncertainty or measurement, not an actual difference, and not of significance. If, on the other

hand, a measured or calculated difference greater than this amount is found, then the difference probably indicates a change in water level and must be further analyzed.

Tide Station at Fernandina Beach, Florida

The tide station at Fernandina (listed as Fernandina Beach, Florida, by NOS) and shown in Figure 2 is among the oldest long-term control tide stations in the nation. The station was installed in 1897, and continuous data are available from June 1897 to June 1924. A long break in the time series occurred in 1924, and the data record resumes from November 1938 and continues to present.

The tide station is installed on a harbor pier in the city of Fernandina Beach, in a standard NOS enclosure that protects the instruments and data recorders. Two stilling wells (white polyvinylchloride tubes) issue below the enclosure (Figure 3). The wider well houses the float mechanism of the ADR, and the narrower well is used by the daily tide observer to lower an electric calibration tape. Water level at this tide station is taken to represent the water level in Cumberland Sound.

Water level in Cumberland Sound is influenced by numerous local and global environmental factors, as described in Chapter 1. Local factors of importance are wind, freshwater runoff, treated wastewater discharges from the paper mills, storm surge, pressure fronts, salinity differences, and seiching. Mann and Mehta (1993) recently gave a general discussion of the difference in water elevation between an enclosed water body, such as an estuary, and the sea connected through a narrow inlet or entrance. The difference in water level between the estuary and sea from all contributions is call "super-elevation" and may be either positive (set up) or negative (set down; negative, for example, by evaporation or by water uptake from the estuary, as for power plant cooling water). Typical values of superelevation for the U.S. coast as reported by Mann and Mehta (1993) appear to be in the range of ±0.5 ft. In general terms, a superelevation arises because the inlet or entrance constriction is highly frictional and prevents the two water bodies from reaching the same level under time-dependent tidal and other forcing. Simply stated, there is never enough time for the enclosed body to adjust to the level in the sea.

An alteration in entrance geometry, such as produced by dredging, would alter the constriction and change the superelevation relation between estuary and sea. If the estuary has a positive superelevation, dredging might allow water to escape to the sea more rapidly and lower the mtl in the estuary; if it has a negative superelevation, the mtl would rise. The value of superelevation could, in principle, change from year to year depending on weather and other factors listed above.

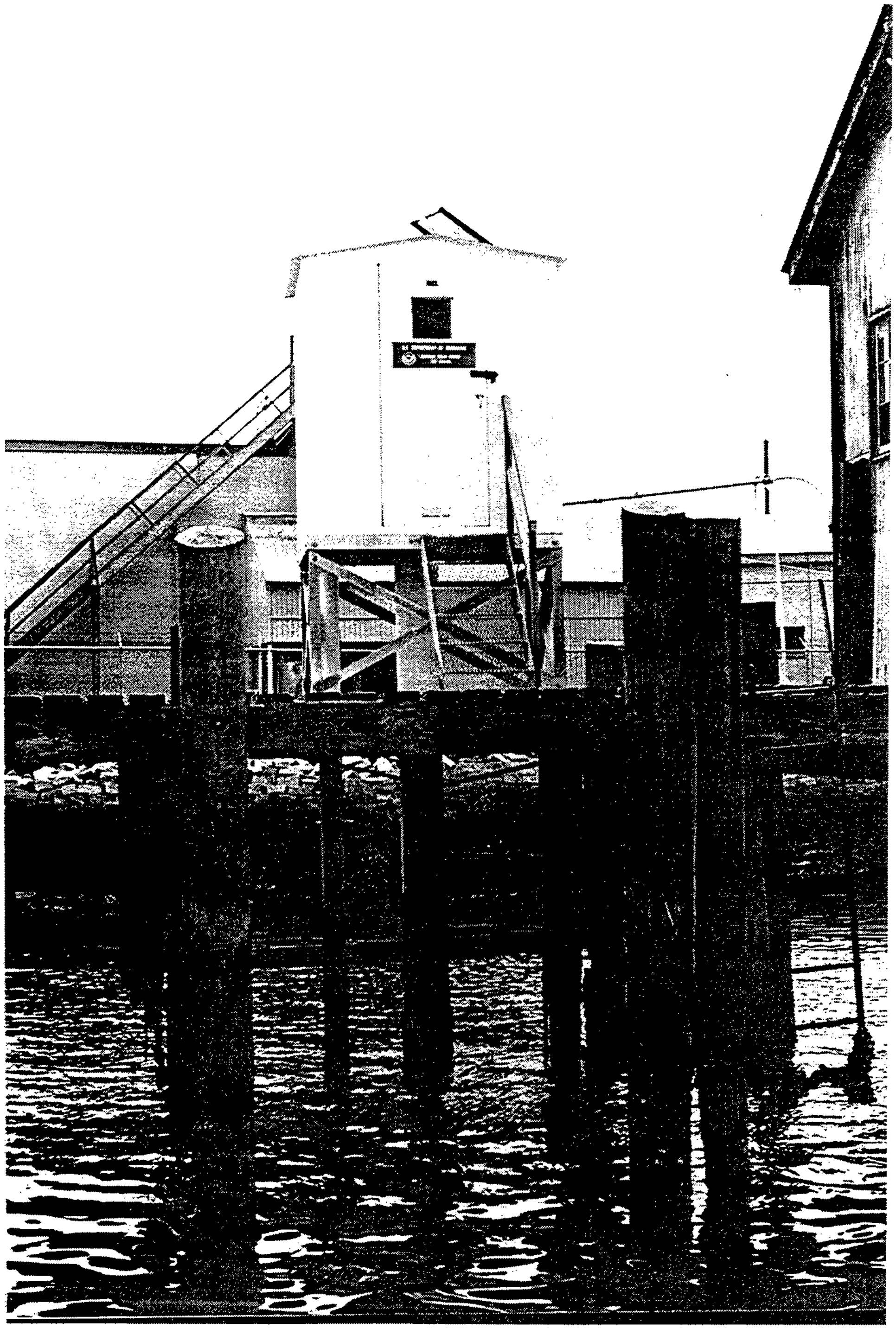

Figure 2. NOS tide station at Fernandina, FL

In the present study, the direct approach is taken of analyzing water-level measurements made at the Fernandina tide station, which is considered to provide a faithful record of water level in Cumberland Sound. Changes in water level are analyzed spatially in comparing water level behavior at neighboring

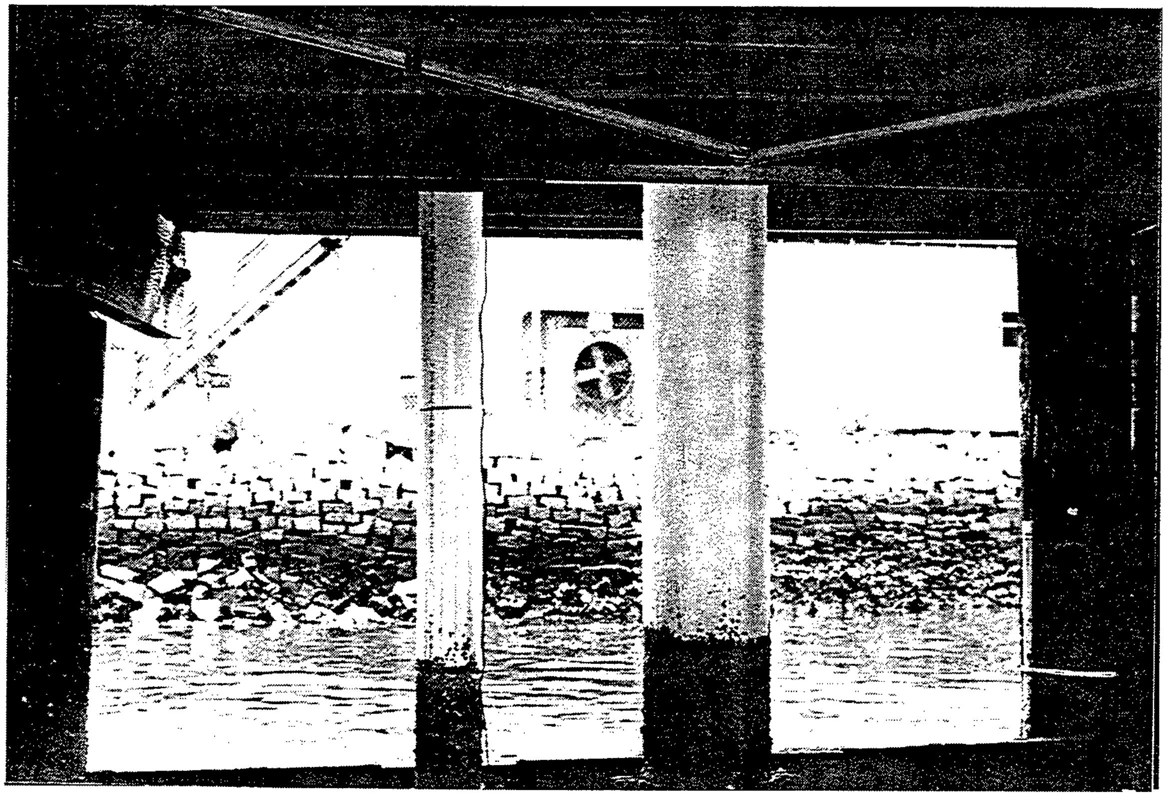

Figure 3. Stilling wells

long-term tide stations and temporally in comparing water level before and after dredging.

3 Water-Level Analysis for Cumberland Sound

This chapter presents the procedures and results of analysis aimed at determining if dredging from 1986-1988 altered the water level in Cumberland Sound. As discussed previously, mtl and tide range are the main parameters considered in the analysis. This chapter is structured in three sections, as follows: (1) regional and long-term relative water-level change at Fernandina Beach and neighboring long-term NOS tide stations (Fort Pulaski, Georgia, to the north and Mayport, Florida, to the south), (2) qualitative comparison of water-level change during and after the time of dredging, and (3) statistical analysis of mtl before and after dredging at the three tide stations.

Regional Relative Sea-Level (rsl) Change

Previous studies of rsl

In this section, selected studies of long-term trends in rsl are described to establish a context for evaluating shorter term trends. The National Research Council (1987) reviewed data on rsl change and found msl to be rising at the majority of tide stations around the coast of the continental United States, except along the Pacific northwest coast. This conclusion followed that obtained in previous publications by NOS personnel (Hicks 1978; Hicks, Debaugh, and Hickman 1983) based on analysis of tide station records.

The most recent NOS compilation of sea-level variation is contained in Lyles, Hickman, and Debaugh (1988), and a summary of their computed long-term trends for msl at selected tide stations is given in Figure 4. The data records are from long-term (primary) NOS tide stations with most beginning in the 1920s or 1930s, although some records go back earlier (e.g., 1856 for New York City) and some began more recently (e.g., 1960 for Sabine Pass, Texas). Figure 4 shows that sea level has been rising relative to the land at the study sites, with average annual rates of 3.0, 1.9, and 2.2 mm for Fort Pulaski, Fernandina, and Mayport, respectively.

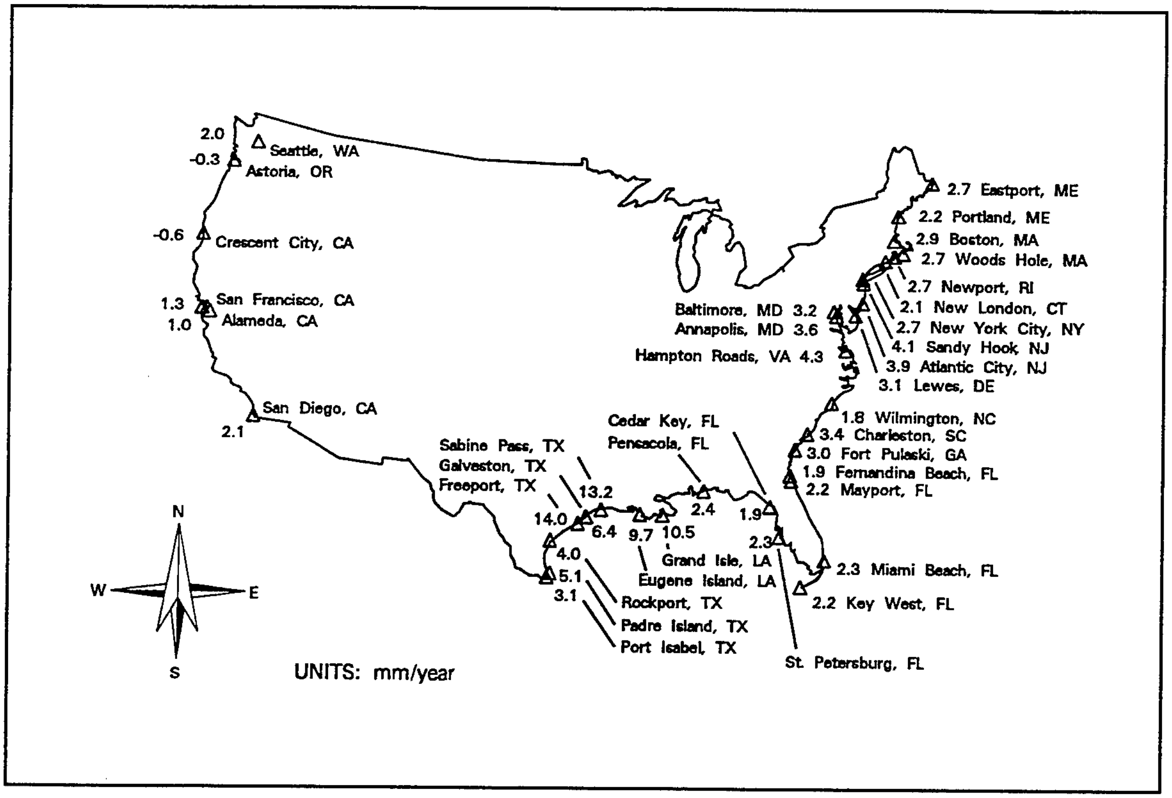

Figure 4. Selected values of local rsl change along the U.S. coast (data taken from Lyles, Hickman, and Debaugh (1988))

Updated long-term trends in rsl

Trends in long-term rsl change were analyzed to bring them to the present and to include the post-dredging period (after 1988). Tide-level measurements were obtained from NOS for this purpose and were available through December 1992. Figures 5 to 8 are plots of the average annual mtl for the subject three stations. The Fernandina station has a longer record than the Fort Pulaski and Mayport stations, and the total record for mtl Fernandina is shown in Figure 6 for completeness. The mtl data are plotted to elevation of their local benchmarks, which are arbitrary, and comparison of stations cannot be made with respect to absolute value of elevation.

Channel realignment and construction and extensive modification of the long jetties at St. Marys Entrance occurred from 1881-1923 (Kraus, Gorman and Pope 1994; their Table 5), and these activities appear to have introduced considerable variability into the tide record at Fernandina prior to 1924. The record of mtl shows a slight trend to decrease between 1898 and 1924.

Because 1939 is the first year of full data available for the three stations (Table 4), analysis and comparisons of water level at the three tide stations will

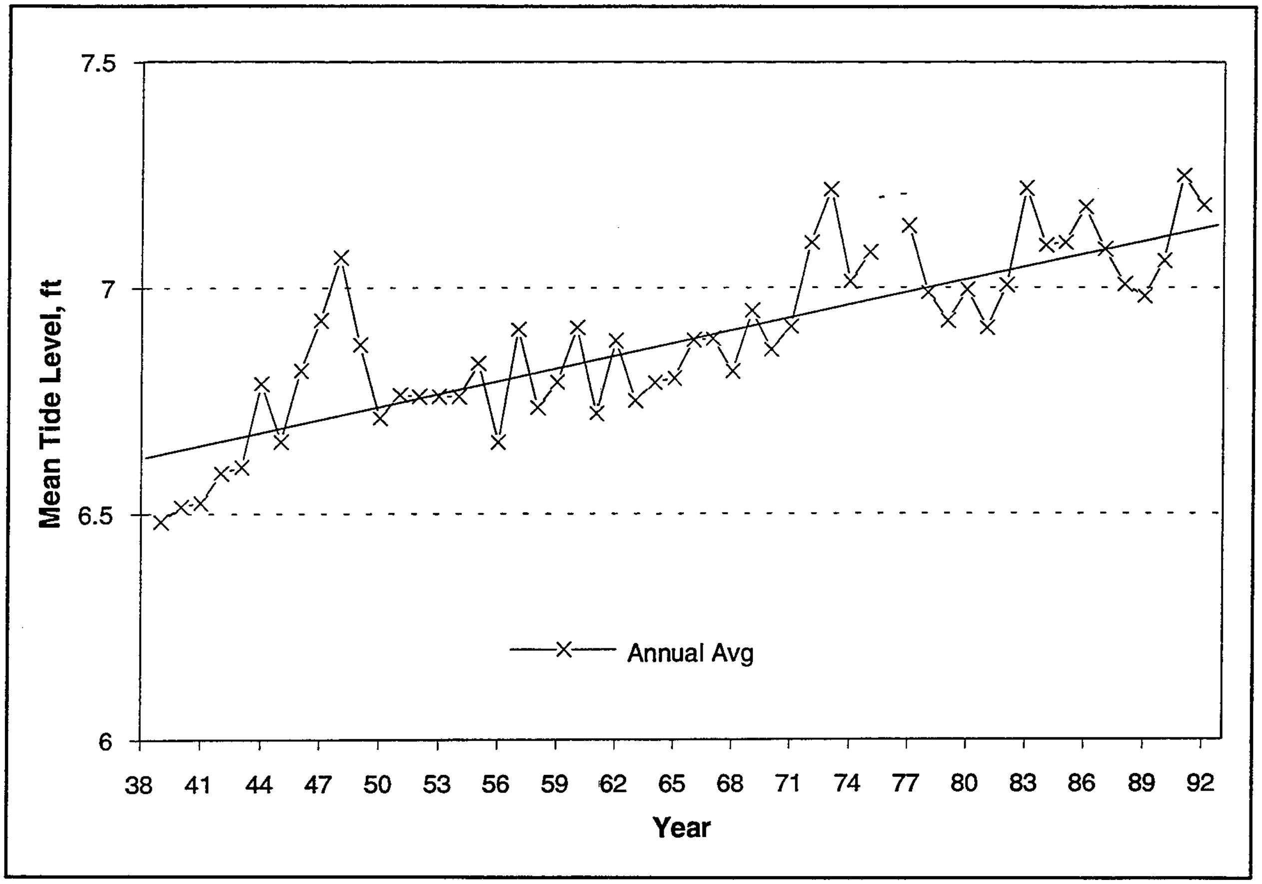

Figure 5. Fort Pulaski, Georgia, mtl, 1939-1992

be made for the full years 1939-1992. Values used are annual averages computed from monthly means obtained from NOS data sheets.

Straight-line fits were made to the mtl data for the three stations for 1939-1992 (Figures 5, 7, and 8), giving slope values of mtl change of 3.0 mm/year at Fort Pulaski, 2.4 mm/year at Fernandina, and 2.3 mm/year at Mayport. These values are similar to those shown in Figure 4 (which are values of change in msl) and differ mainly by inclusion of 7 years of more recent data. Assuming msl and mtl have the same rate of change, the annual rate of change of mtl increased at Fernandina from 1.9 to 2.4 m, whereas mtl remained constant at Fort Pulaski and increased slightly at Mayport (2.2 to 2.4 mm). Because of the recent increase in rate of change of mtl, further examination of the water-level data at Fernandina is warranted.

Mean values of the mtl records over 1939-1992 were calculated and removed to enable direct comparison of records. Demeaned annual mtl values for the three stations are plotted in Figure 9. For most years, mtl among the three stations tracks closely. At different times, different stations show a relative maximum greater than that of the other stations. For example, in 1948 and 1960,

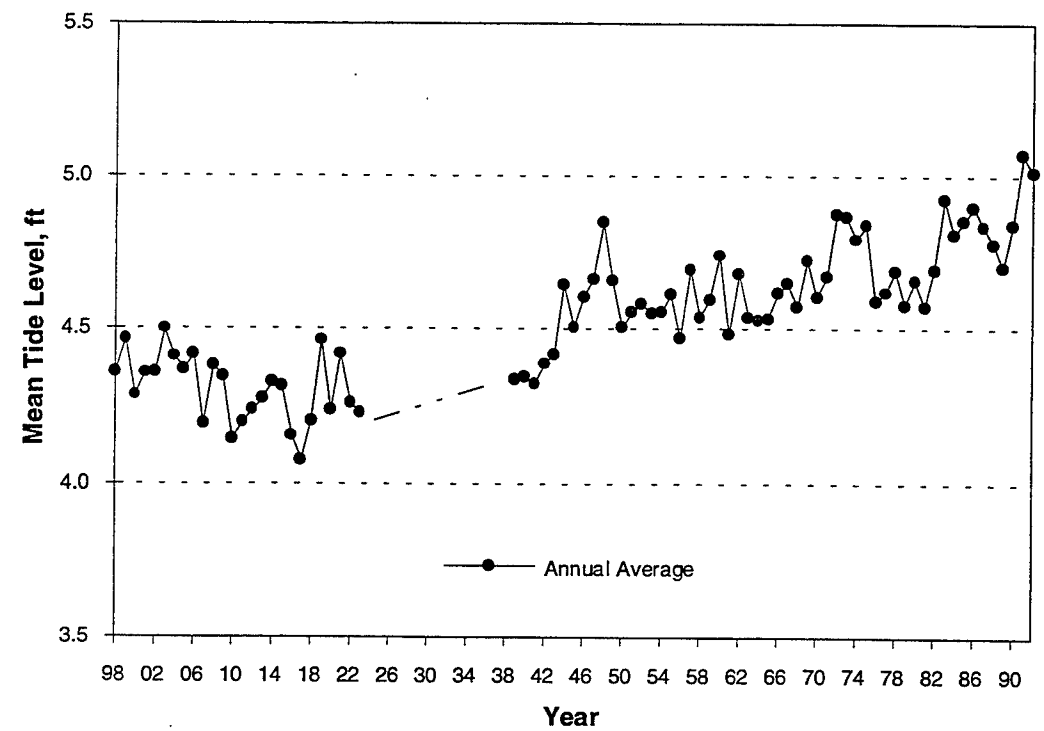

Figure 6. Fernandina Beach, Florida, mtl, 1898-1992

Mayport had peak mtl greater than the other stations, whereas in 1972 and 1976-1985, msl at Fort Pulaski peaked above the other stations, and Fernandina peaked higher in 1944 and in 1991 and 1992. River discharges at the Fort Pulaski and Fernandina tide stations could significantly alter tide level at these stations independently of tide level change occurring at other stations, and river discharge is an expected cause of much of the change in relative position of corresponding points on the mtl curves.

Updated values of tide range

Tide range is plotted in Figures 10-13 for Fort Pulaski, Fernandina, and Mayport, with Figure 11 showing the full record for Fernandina, and the other figures plotted for 1939-1992. Figure 11 shows that the tide range at Fernandina at the turn of the century, a time of considerable construction at St. Marys Entrance, was considerably more variable than the post-1939 time frame. Typically, at any tide station, tide range is smoothly varying as compared to tidal datums such as mtl.

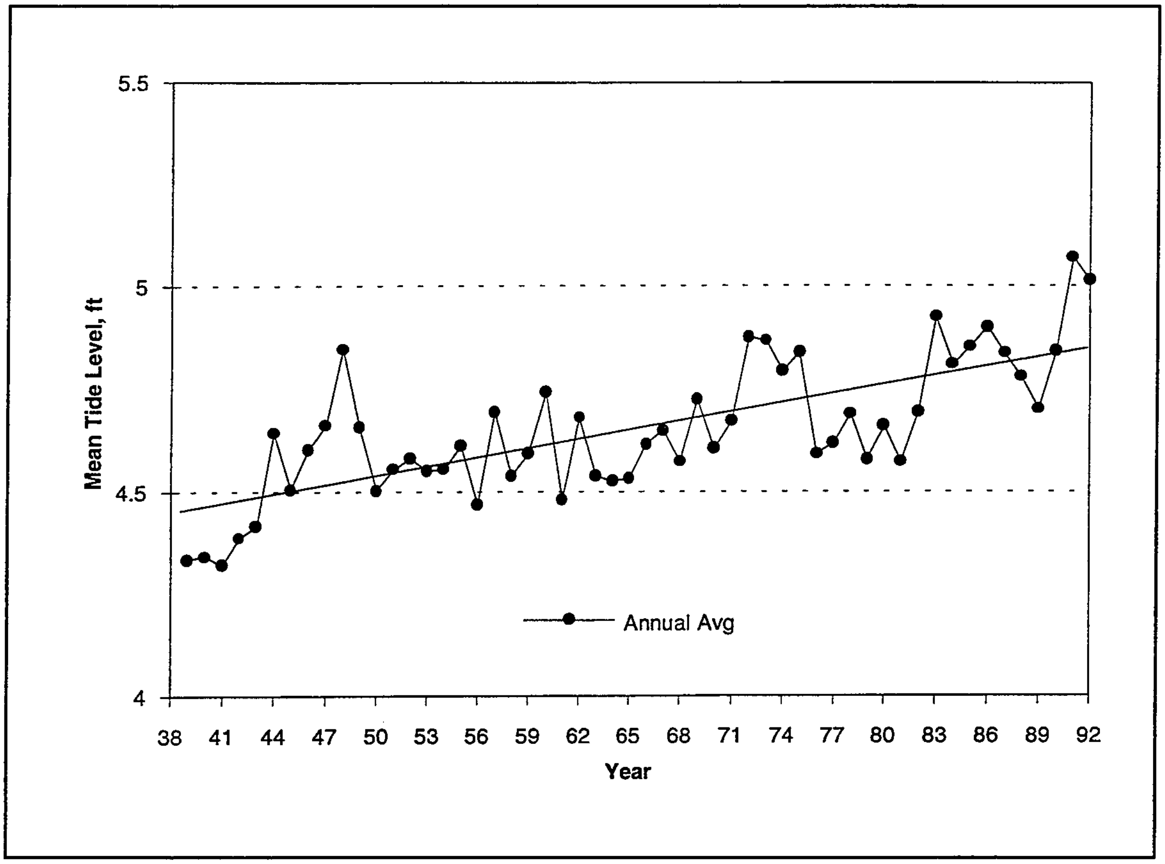

Figure 7. Fernandina Beach, Florida, mtl, 1939-1992

Demeaned tide range for the three stations is plotted in Figure 14. The phases of the range track well and show an approximate 19-year periodicity, which is the origin of the 19-year tidal epoch calculation procedure used by NOS in defining tidal datums. Visual inspection indicates a periodicity in range between approximately 18 and 21 years, which corresponds to the 19-year periodicity of the diurnal inequality. The post-dredging record continues the general cyclical trend.

The demeaned range at Fernandina is typically bracketed by the demeaned ranges of the other two stations. All stations were in the phase of minimum range during the 1986-1988 interval of intensive dredging at St. Marys Entrance and Cumberland Sound, but no abnormal change in range interrelationship is seen during or after that interval.

Mean high water

The tidal datum mhw is the average of all high-water heights and is listed on NOS data sheets or can also be readily obtained from values of mtl and tide range. An increase in mhw represents a more severe environmental change in water level because it is an extreme that occurs daily.

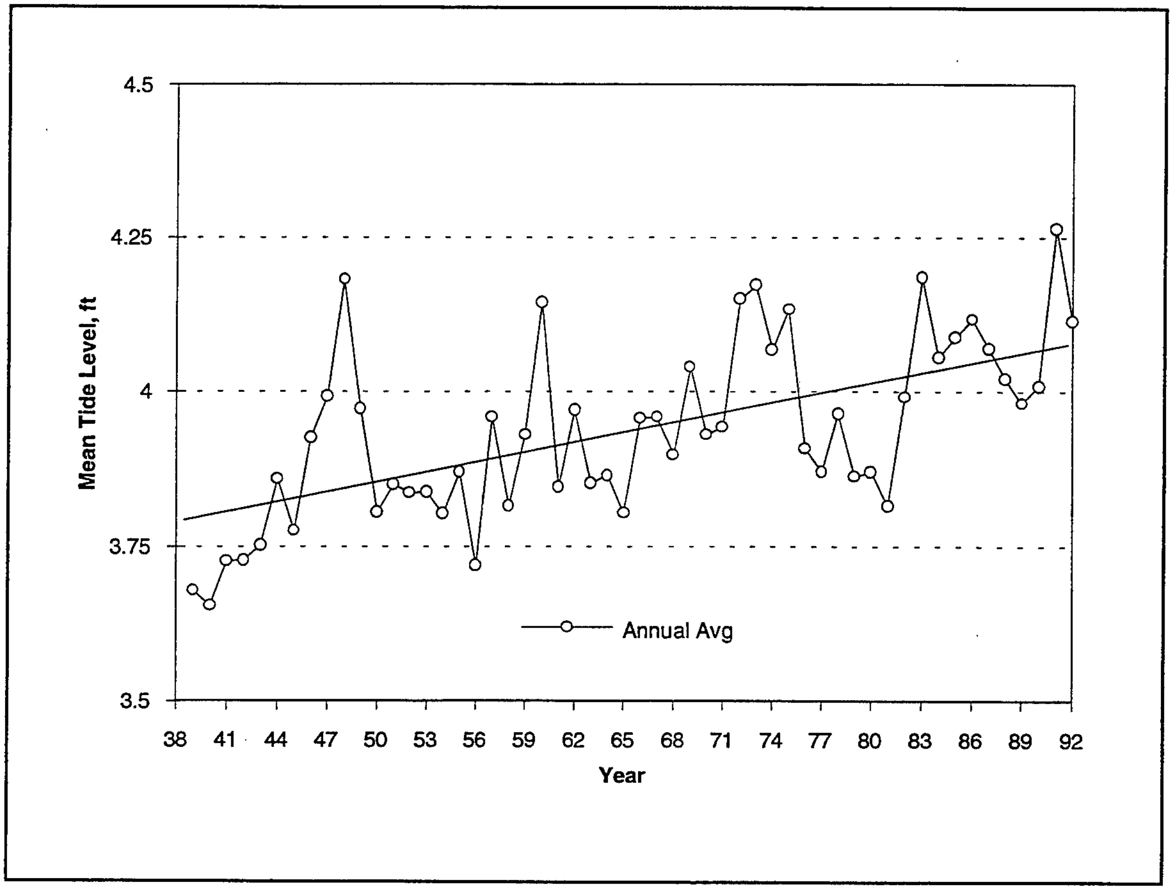

Figure 8. Mayport, Florida, mtl, 1939-1992

Figure 15 shows annual values of mhw for 1939-1992 for the three stations, each plotted to its local benchmark to distinguish the curves. Values of mhw increase through time, and local maxima and minima track well for the three stations. For example, prominent local maxima occur at the three stations in the years 1944, 1948, 1957, 1960, 1983, and 1991. An exception is the interval 1972-1975, when Fernandina and Mayport show a broad local maximum that does not appear at Fort Pulaski. In connection with this broad maximum, mhw at Fort Pulaski increased over 1974-1976, whereas mhw at the other two stations remained nearly constant and decreased.

During the 4-year interval 1986-1989, which includes the subject dredging, mhw undergoes a uniform decrease at the three stations, and in 1991 it rises to a local maximum at all stations, whereafter mhw decreases in 1992. No influence of dredging at Fernandina is evident in the mhw record with respect to trend, although the amount of increase at Fernandina over 1989-1991 is slightly greater than at the other two stations.

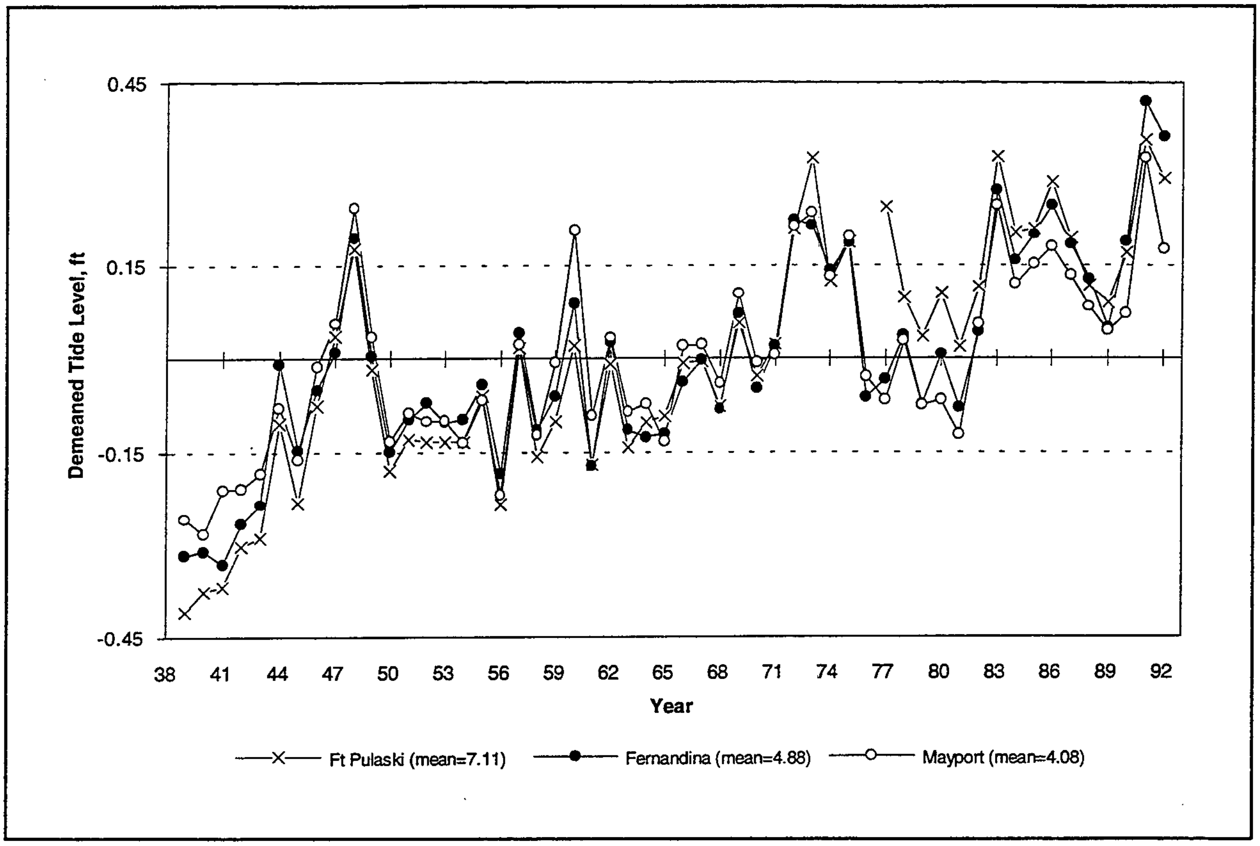

Figure 9. Comparison, demeaned mtl, 1939-1992

Table 4
Monthly Water-Level Data Available for the Three Analyzed Stations

Fort Pulaski	Fernandina Beach	Mayport
Jul 1935 - Jan 1943	Jun 1897 - Jun 1924	Jan 1895 - Dec 1897
Apr 1943 - Aug 1943	Nov 1938 - May 1993	May 1928 - Jul 1992
Nov 1943 - Jan 1974[1]		Nov 1992 - Apr 1993
Jul 1974 - Dec 1975		
May 1977 - Jun 1977		
Nov 1977 - May 1993		

[1] Values of tide range missing for Feb - Jun 1974.

Seasonal changes

Tide level and range exhibit seasonal variability along the coast and among different coasts. On the east coast of the United States it is common, but not

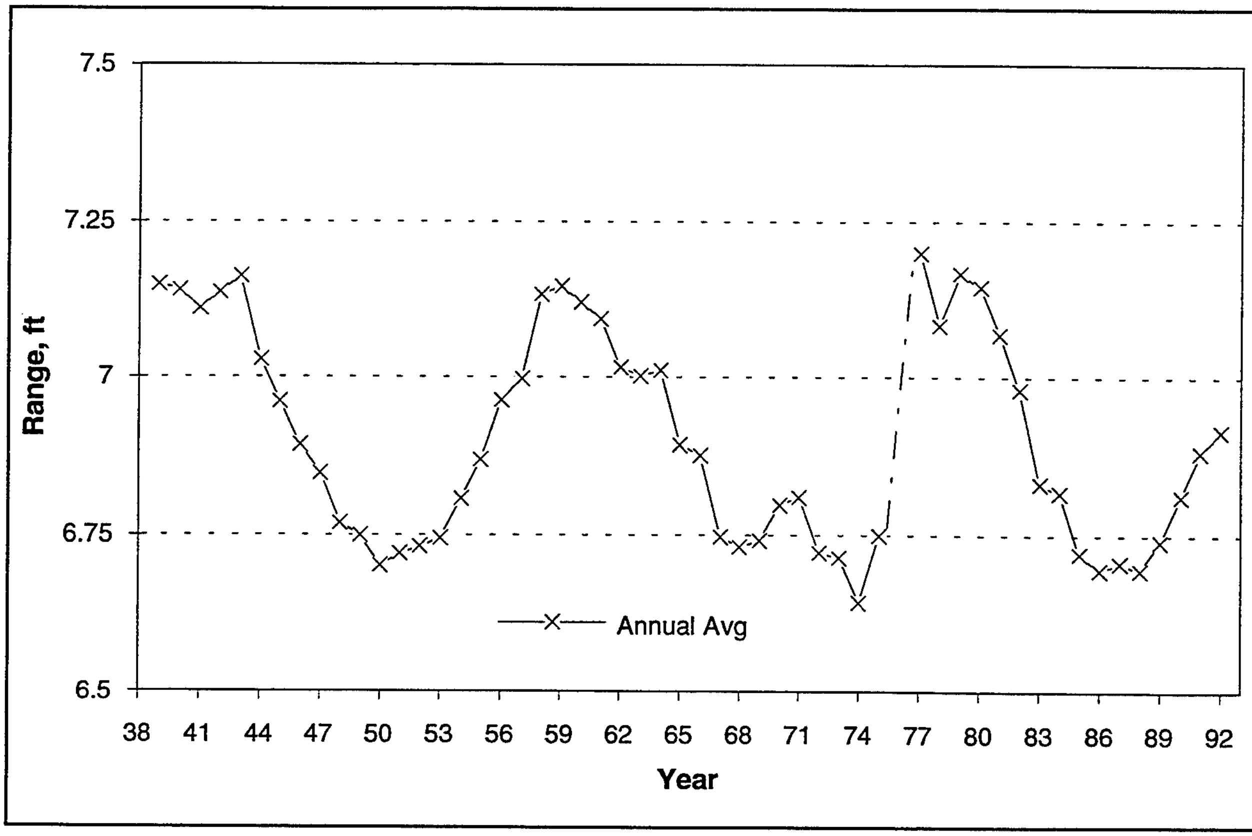

Figure 10. Fort Pulaski, Georgia, range, 1939-1992

ubiquitous, for water level to attain either a relative or absolute maximum in the last quarter of the calendar year. At Fort Pulaski, Fernandina, and Mayport, and absolute maximum typically occurs in October.

Figures 16-18 plot monthly average values of mtl for Fernandina for the intervals 1980-1984, 1985-1989, and 1989-1992. These plots demonstrate the temporal variability in short-term statistics of water level, for which contributions from storms, rain (or drought), wind, and river and effluent discharge would have great influence. For example, Figure 16 shows that water levels in October of 1980-1984, an interval of little dredging, varied by about 0.65 ft. During the interval of dredging (Figure 17) variation in mtl in October decreased slightly to about 0.60 ft, and in the post-dredging interval (Figure 18) the variation in October decreased further to about 0.45 ft. In contrast, variability increased during the summer, in particular, June, during the post-dredging period as compared to the previous two time intervals examined. Monthly values of mtl in 1992 tend to lie above those of other years.

Tide range at Fernandina for the pre-, during-, and post-dredging time intervals is plotted in Figures 19-21. Considerable variation among years is seen, but the spread in values for range is less than that for mtl. Tide range at Fernandina is at a minimum in October and a broad maximum in summer. The

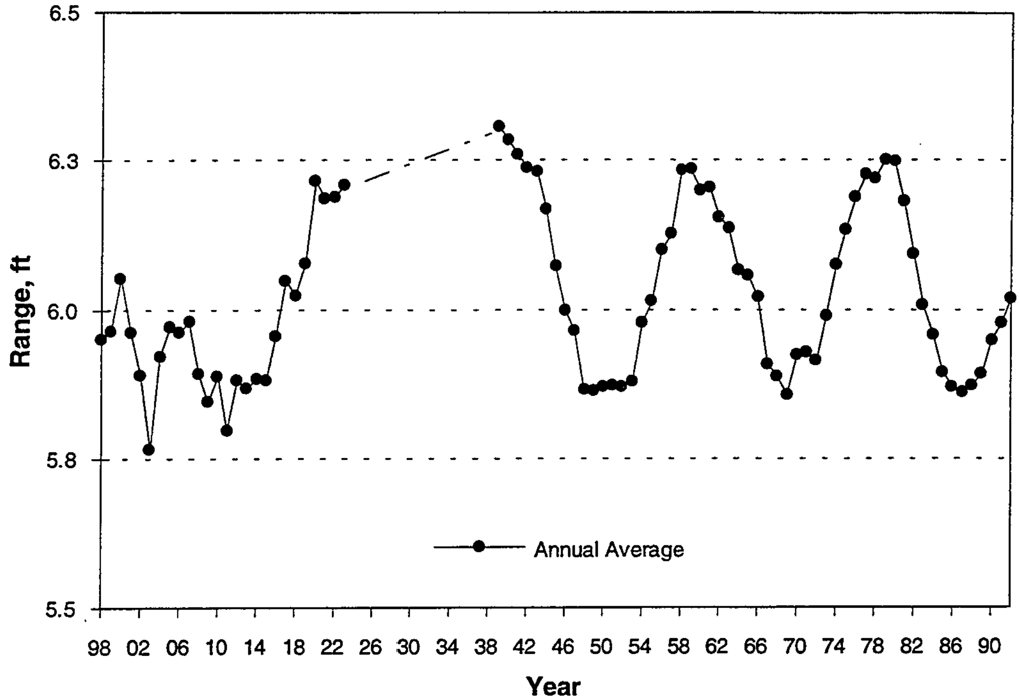

Figure 11. Fernandina Beach, Florida, range, 1898-1992

spread in range values is typically less in the time intervals during and after dredging, except for July and August of 1992, when the range increased.

Water Level Around the Time of Dredging

Figures 22 and 23 plot values of demeaned annual mtl and annual tide range for the three tide stations for the time interval 1984-1992 and are presented for focusing on the subject dredging time interval of 1986-1988. As discussed in the previous sections, trends in mtl, tide range, and mhw track well before, during, and after dredging. Figure 22 indicates that mtl for Fernandina typically undergoes greater variation, lying below values at the other two stations during recent years of decrease and above during years of increase in water level, with a notable exception occurring in 1992.

Figure 23 shows that in recent time the tide range at Fernandina has had a strong tendency to lie between the ranges at Fort Pulaski and Mayport, with Fort Pulaski having maximum change in range and Mayport having minimum change among the three stations.

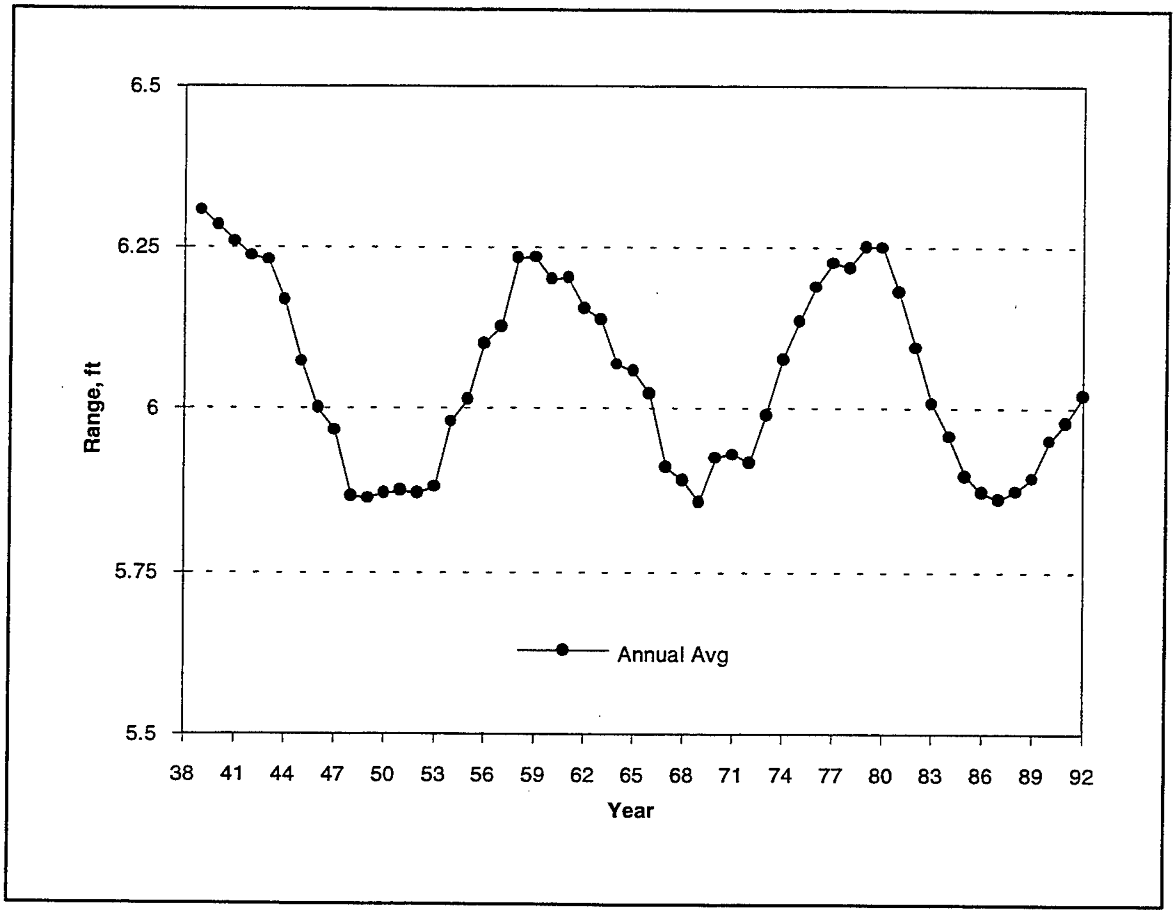

Figure 12. Fernandina Beach, Florida, range, 1939-1992

Qualitative and quantitative comparisons of the time records of mtl, tide range, and mhw as described in this and previous sections indicate that water level has not increased in Cumberland Sound. This conclusion is examined statistically in the next session.

Statistical Hypothesis Test

Analysis results described above indicate that water level at the Fernandina tide station, and hence in Cumberland Sound, did not change as a result of the 1986-1988 dredging. This overall conclusion is based mainly on qualitative comparisons of trends in change and in absolute values of mtl, tide range, and mhw. Because the conclusion of no change in water level due to dredging lies somewhat in the realm of interpretation, an objective criterion was sought, as provided by statistical hypothesis testing.

A two-sample Student's *t*-test was applied as an objective measure to determine whether there was a stastically significant difference in yearly mtl between the pre-1986 and post-1986 measurements. If the differences in the

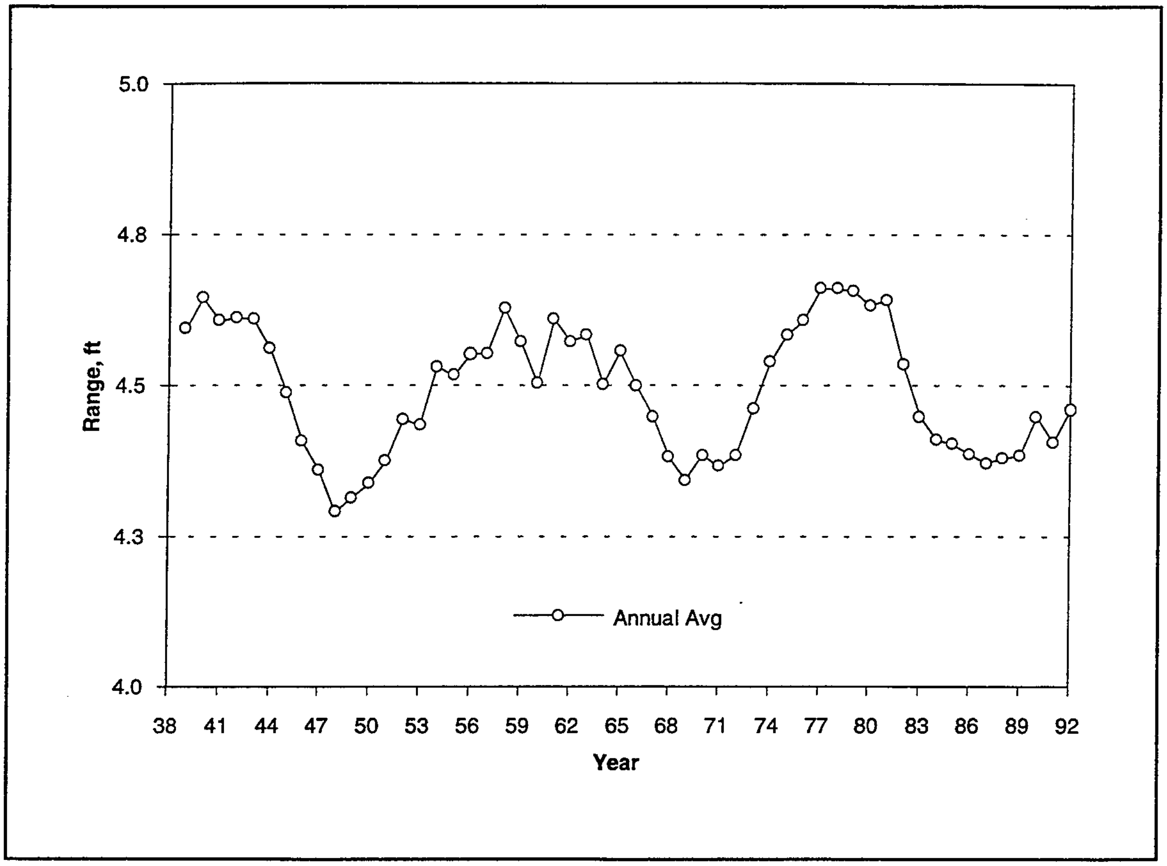

Figure 13. Mayport, Florida, range, 1939-1992

expected yearly means for pre-1986 and post-1986 data are not statistically significant, then any difference observed may be attributed to chance and not to dredging. The hypothesis test was done in three parts:

a. Exploratory data analysis.

b. Hypothesis testing.

c. Sensitivity analysis.

The data employed were yearly values of mtl from 1939 to 1992 for Fort Pulaski, Georgia, Fernandina, Florida, and Mayport, Florida. The first sample for each data set consisted of the values for 1939-1985, representing the time period before the subject (1986-1988) dredging in Cumberland Sound and St. Marys Entrance. The second sample consisted of values from 1986-1992, representing the time period during and after dredging.

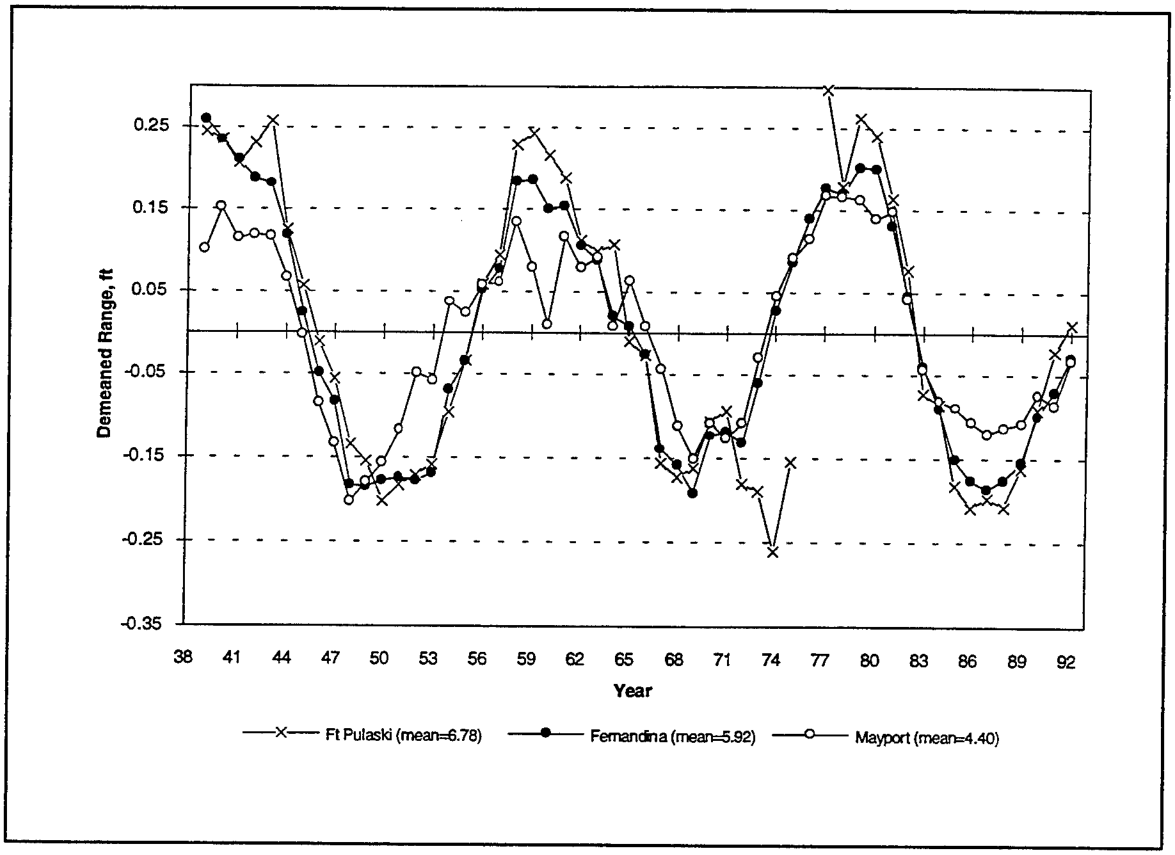

Figure 14. Comparison, demeaned range, 1939-1992

Exploratory data analysis

The classical two-sample Student's *t*-test is based on three assumptions: (1) standard deviations of the populations from which the samples were taken are the same; (2) populations from which the samples were taken have a Gaussian distribution; and (3) sample data are uncorrelated.

The *t*-test is robust against departures from the first two assumptions, but it is sensitive to the presence of correlations within the data (Miller and Freund 1985). Because population standard deviations are never precisely known, Assumption 1 is considered valid if the sample standard deviations are not significantly different. The pre-1986 sample standard deviation for Fort Pulaski is 0.18 and the post-1986 sample standard deviation is 0.10. The pre-1986 sample standard deviation for Fernandina is 0.14 and the post-1986 sample standard deviation is also 0.14. The pre-1986 sample standard deviation for Mayport is 0.14 and the post-1986 sample standard deviation is 0.10. The differences in these standard deviations are not significant, indicating that Assumption 1 is valid.

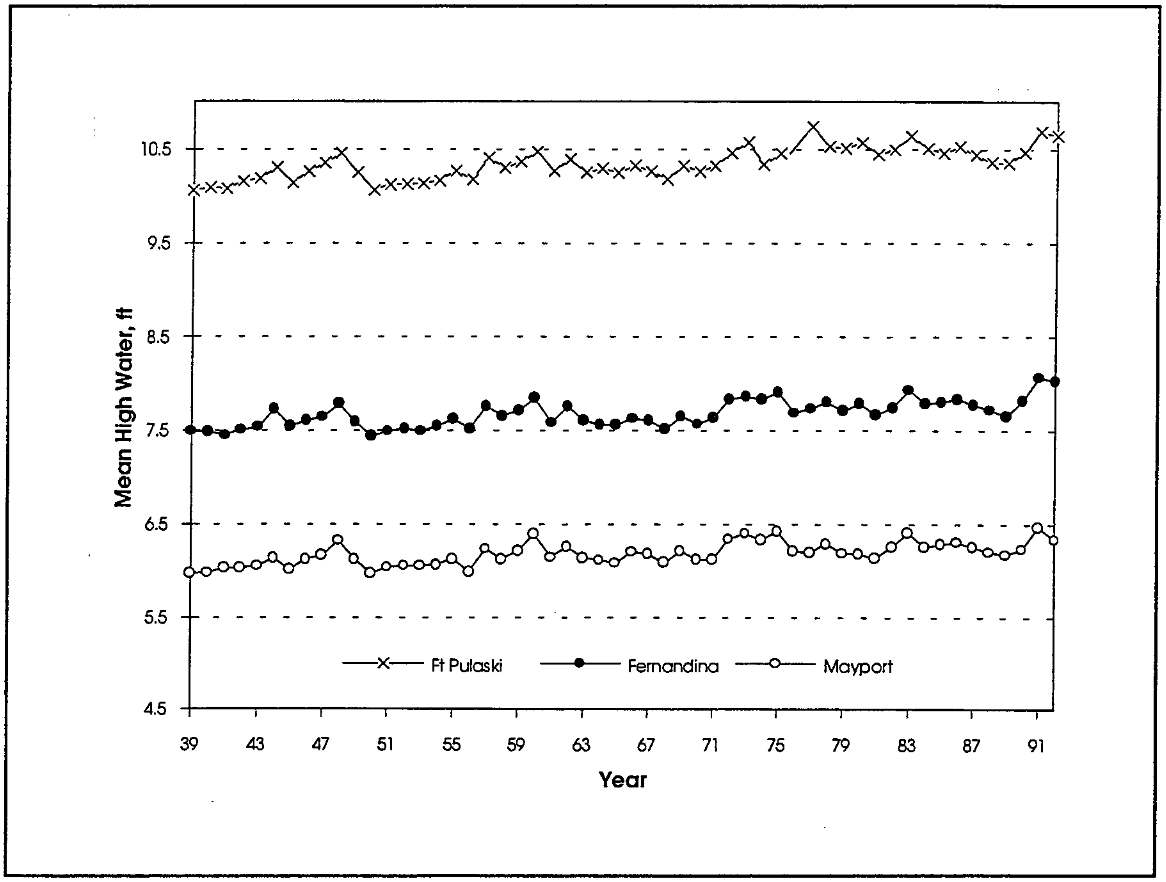

Figure 15. Comparison, mhw, 1939-1992

Plots of annual mtl for each of the three stations from 1939-1992 are given in Figures 5, 7, and 8, and show a trend of rsl rise over the entire time interval. A linear least-squares regression was done and the trend subtracted from the data, with the detrended data called the "residual." The residuals after removing the linear trend still appeared to have the same standard deviation for pre-1986 and post-1986 values (Figure 24). Assumption 2 was tested for the residuals using probability plots. The probability plots, given in Figures 25 to 27, showed that the residuals, indicated by dots, approximate the Gaussian distribution as given by the straight line, almost through the distance of plus and minus the second standard quantile, indicating that Assumption 2 is sufficiently valid to use the *t*-test. The larger deviations in residuals in the tails of the distributions are on the order of 0.05 ft, and, therefore, below the level of confident measurement.

Assumption 3 was tested for the residuals by calculating the correlation coefficients (Figure 28). The values indicated that the residuals are correlated with a correlation length of approximately 3.5 to 4 years, indicating that Assumption 3 is violated. A correlation length of 4 years signifies that measurements separated by less than 4 years are not independent (given the assumption of a Gaussian distribution). The length is interpreted as indicating that astronomical tidal constituents and forcing caused by periodic changes in

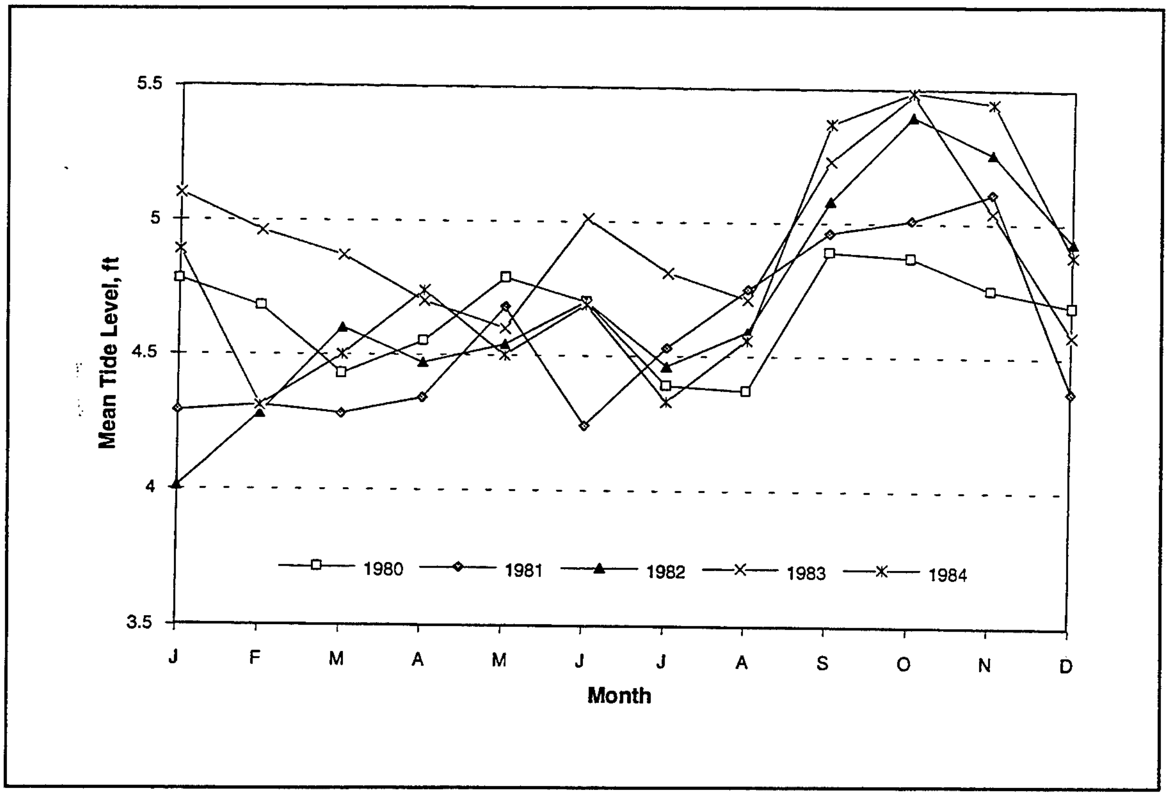

Figure 16. Fernandina Beach, Florida, mtl, 1980-1984

weather patterns with periods less than 4 years are strongly correlated for the two time intervals (pre- and post-dredging) under consideration. Such a correlation is reasonable because the leading tidal constituents and basic cyclical weather patterns do not greatly change in time. Because of the existence of the correlation, a correlated Student's *t*-test developed by Borgman (1991) was used to perform a hypothesis test on the residuals of mtl.

Correlated Student's *t*-test

A central parameter in calculating a *t*-statistic is the number of degrees of freedom. The number of degrees of freedom *df* for independent data is determined as

$$df = n_1 + n_2 - 2 \tag{1}$$

where n_1 is the number of data points in the first sample, and n_2 is the number of data points in the second sample being compared. The number of degrees of freedom is two less than the total number of samples because one degree of freedom is eliminated in calculating the mean and a second eliminated in calculating the standard deviation.

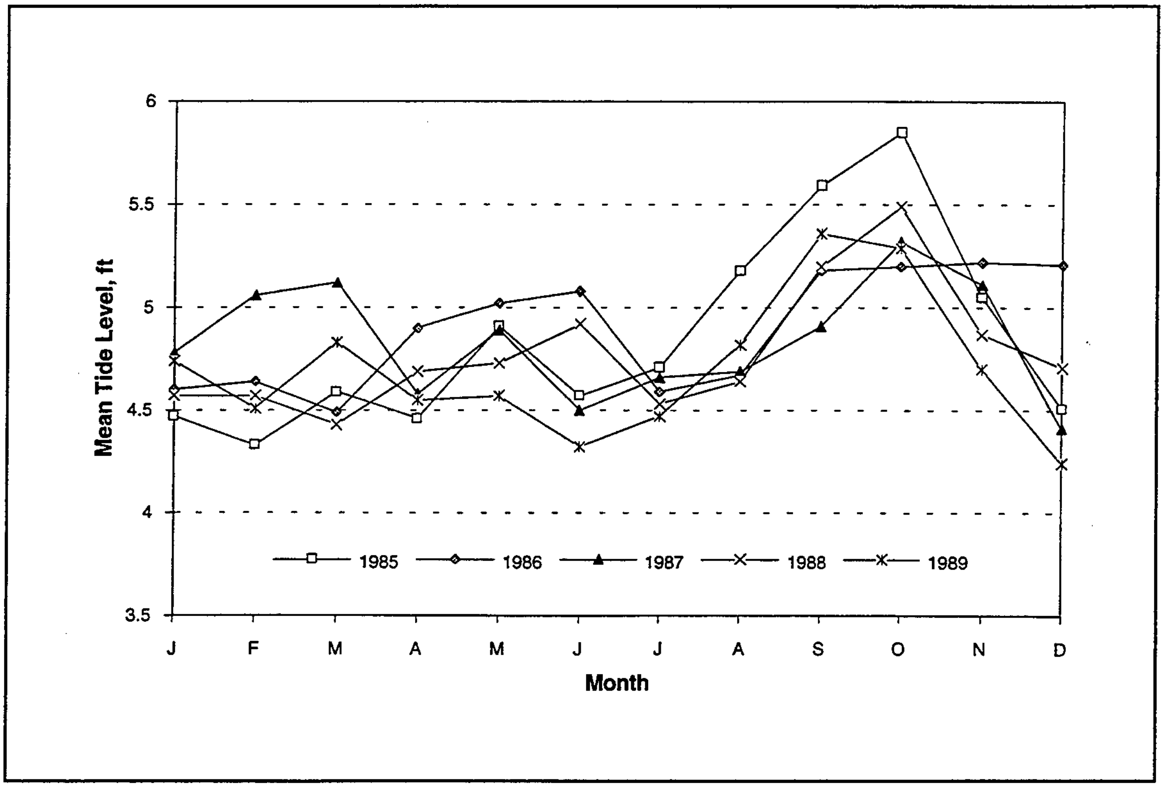

Figure 17. Fernandina Beach, Florida, mtl, 1985-1989

The number of degrees of freedom for correlated data may be less than that for independent data. The correlated Student's *t*-test calculates the degrees of freedom using an eigenvector decomposition of the correlation coefficient matrix. One result of this decomposition is a diagonal matrix containing the eigenvalues corresponding to the eigenvectors. In practice, some of these eigenvalues will be zero or nearly zero. The number of significantly non-zero eigenvalues is given by ν, and the number of degrees of freedom for correlated data is found as

$$df = \nu - 2 \tag{2}$$

where

$$\nu \le n_1 + n_2 \tag{3}$$

The new value for the degrees of freedom is then used to calculate the *t*-statistics involved in hypothesis testing.

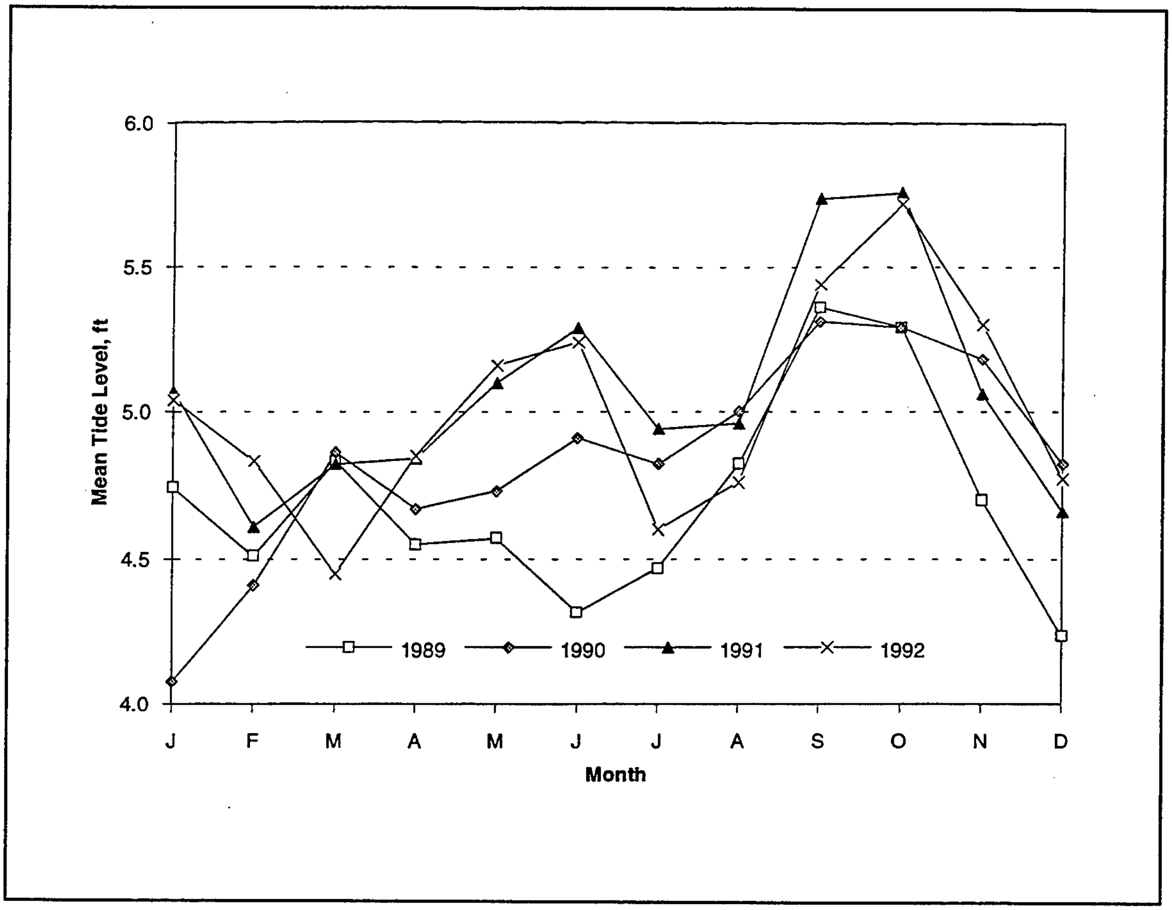

Figure 18. Fernandina Beach, Florida, mtl, 1989-1992

Hypothesis testing

A two-tailed, two-sample correlated *t*-test was performed on the residuals of mtl for all three data sets. The null hypothesis was that the mean of the pre-1986 residual data is the same as the mean of the post-1986 residual data. The alternative hypothesis was that the two means are significantly different. To perform the test, a *t*-value calculated for the data is compared to the critical *t*-value which depends on the number of independent samples. The level of significance of the test, which represents the probability of rejecting the null hypothesis when it is really true, was set at 0.01. The null hypothesis is accepted if the absolute value of the calculated *t*-value is less than the critical *t*-value; otherwise, the alternative hypothesis is accepted.

The calculated *t*-value for the Fernandina residuals is -1.06 and the critical *t*-value is 3.37. As a result, the null hypothesis that the means of mtl for the pre-1986 and the post-1986 residual data are the same at Fernandina was accepted, and the alternative hypothesis that the means are significantly different was rejected.

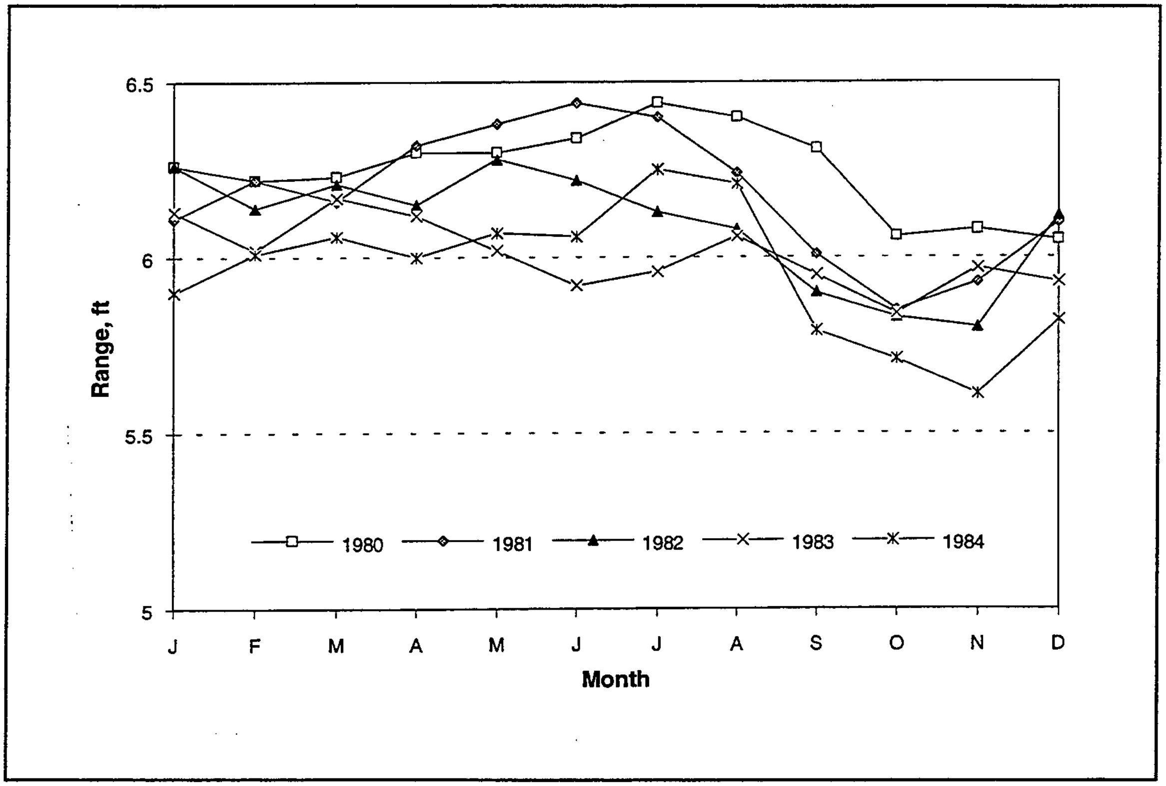

Figure 19. Fernandina Beach, Florida, range, 1980-1984

The correlated *t*-test was also run for the data from Mayport and Fort Pulaski, where no effects of the dredging were expected, as a check on the validity of the test. The null hypothesis that the means of the residuals in mtl for the pre-1986 and post-1986 tidal residuals are the same was accepted at both of these stations. Results are given in Appendix A.

Sensitivity analysis fo the *t*-test

The final step was to determine how much of an increase in the post-1986 average of the residuals would be needed in order to reject the null hypothesis and accept the alternative hypothesis. This procedure will give an indication of the sensitivity of the test to small increases in mtl. The test would be relatively insensitive of tidal level changes if a large increase in the average mean tidal level is needed to reject the null hypothesis, and this insensitivity would call into question conclusions from the hypothesis tests. In contrast, the test would be sensitive to tidal level changes if a small increase in the post-1986 averages is needed to reject the null hypothesis, and would strengthen confidence in the statistical test.

Increased average mtl values for the post-1986 residuals needed to reject the null hypothesis were found to be 0.20 ft at Fort Pulaski, 0.15 ft at Fernandina,

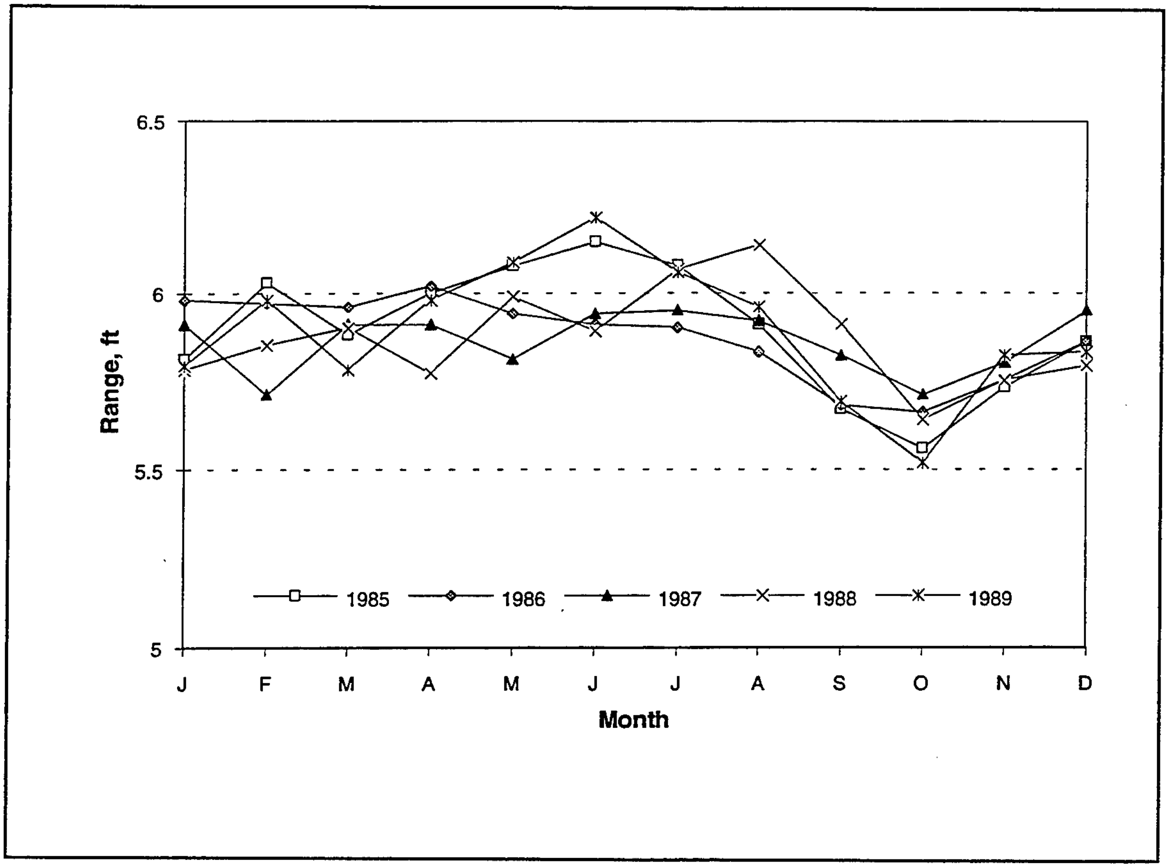

Figure 20. Fernandina Beach, Florida, range, 1985-1989

and 0.18 ft at Mayport. Results are given in Appendix B. These relatively small values indicate that the test is sensitive to small changes in mtl and strengthens confidence in the conclusions from the test. It is noted that changes in the value of mtl needed to reject the hypothesis are greater than the estimated error in measurment (±0.05 ft) of an annual water level datum obtained in Chapter 2, which is a physically sensible result in that changes being sought through statistical calculations are larger than those that can be discriminated through measurement.

The results of the correlated Student's *t*-test indicate that at the 0.01 significance level, there is no statistically significant difference in the residual mean tidal level between the pre-1986 values and the post-1986 values at Fernandina. Measured mean tidal levels are not the same for pre-1986 and post-1986 data at any of the three stations used in this study. Differences in the measured tidal levels can be attributed to the long-term trend in relative water-level change observed at the three stations.

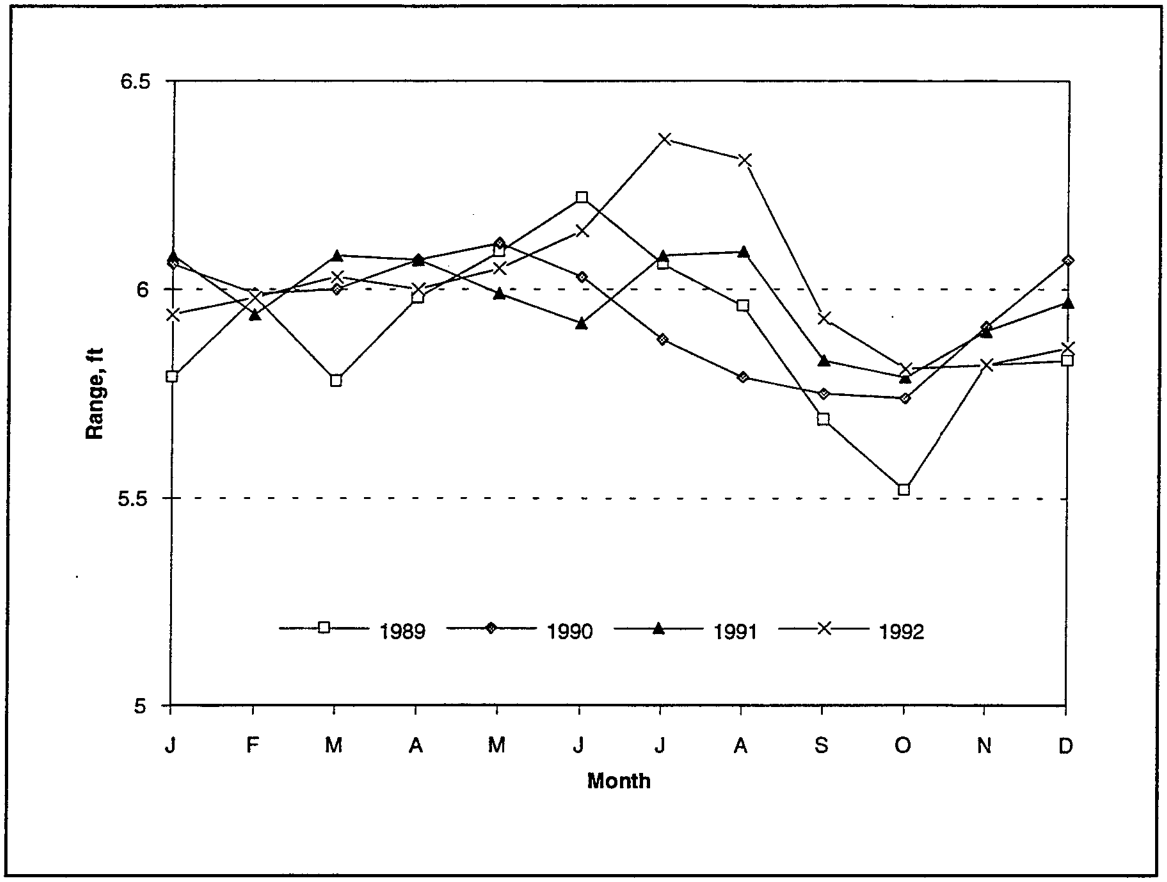

Figure 21. Fernandina Beach, Florida, range, 1989-1992

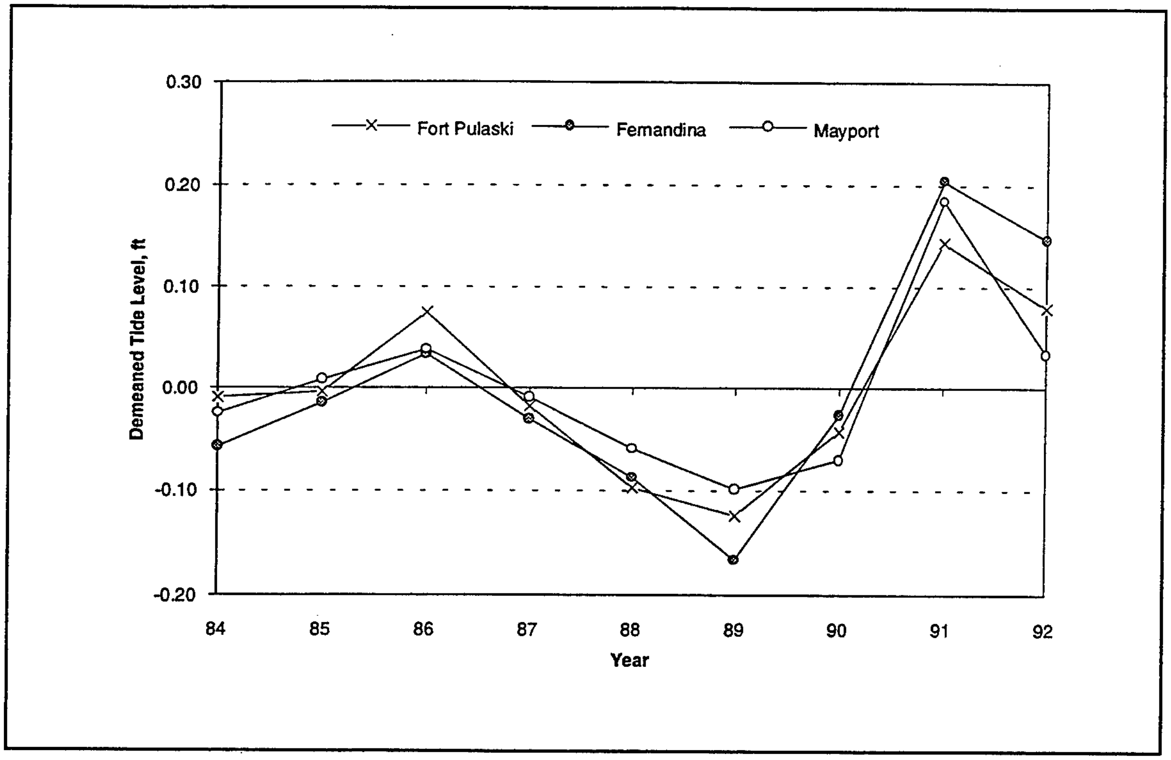

Figure 22. Comparison, demeaned mtl, 1984-1992

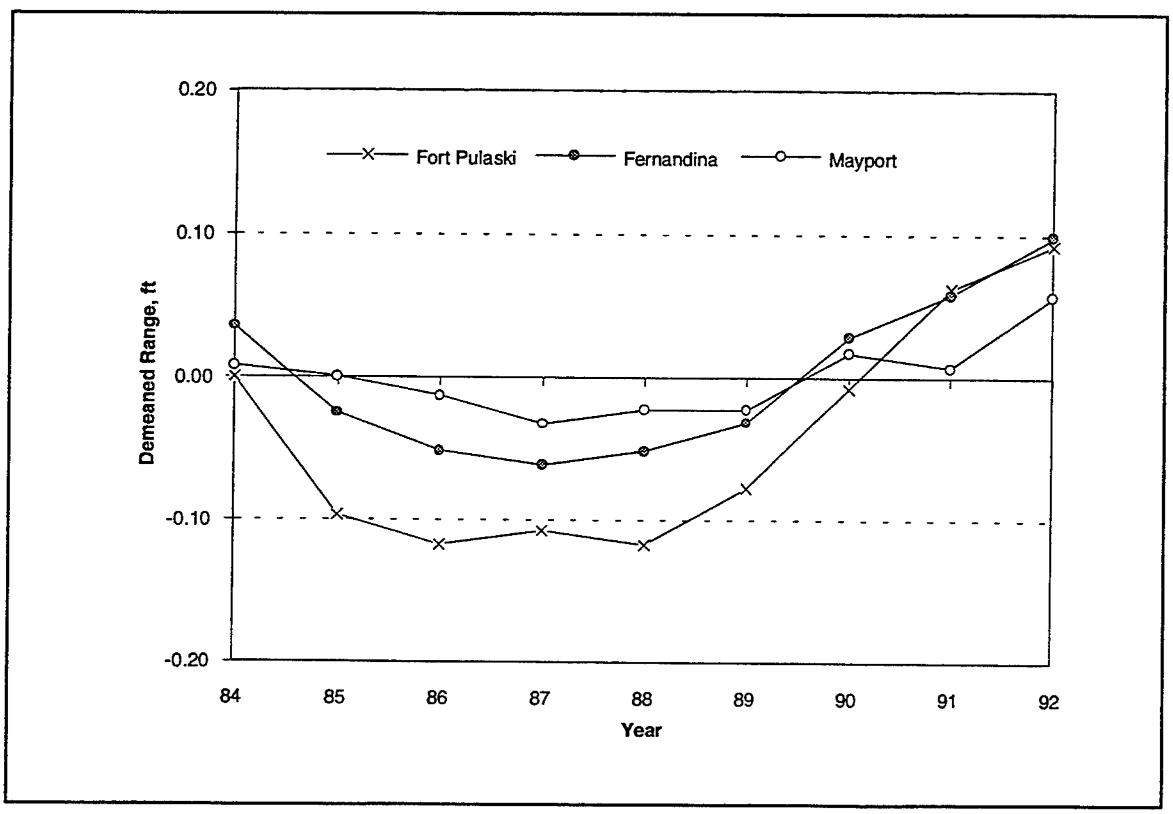

Figure 23. Comparison, demeaned range, 1984-1992

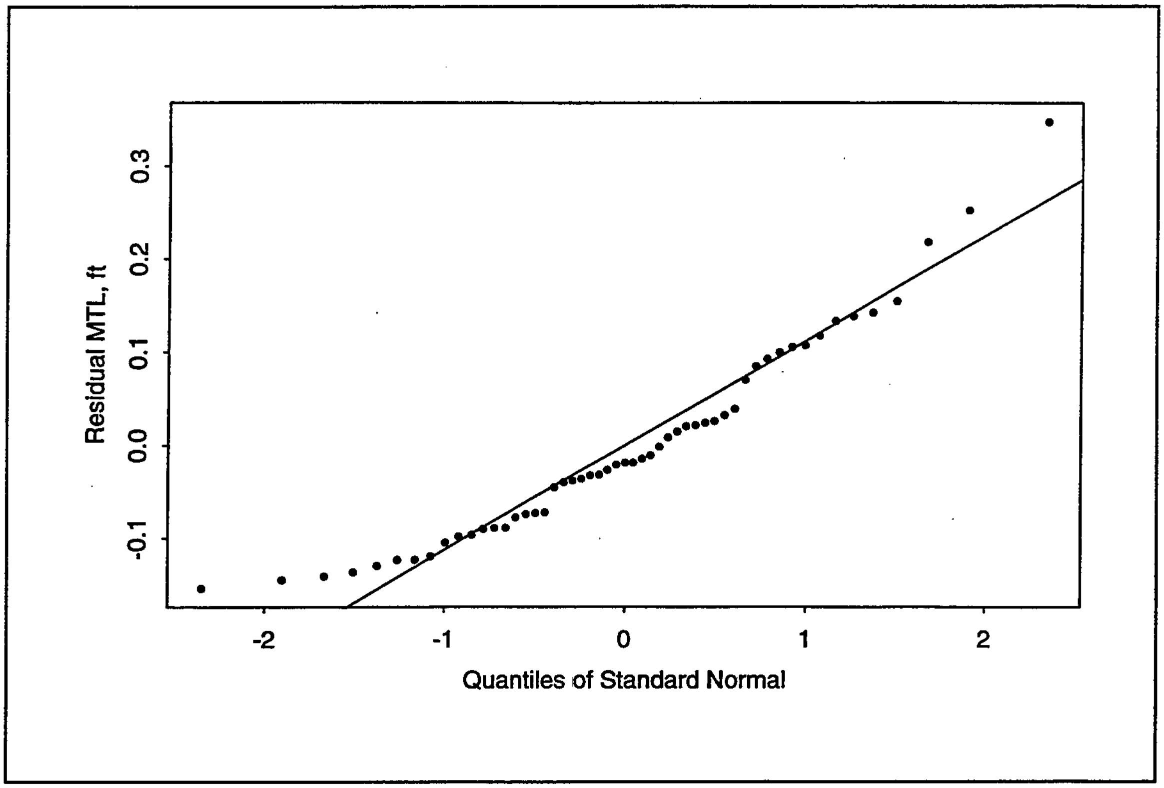

Figure 24. Residual annual mtl after removing linear trend for all three stations

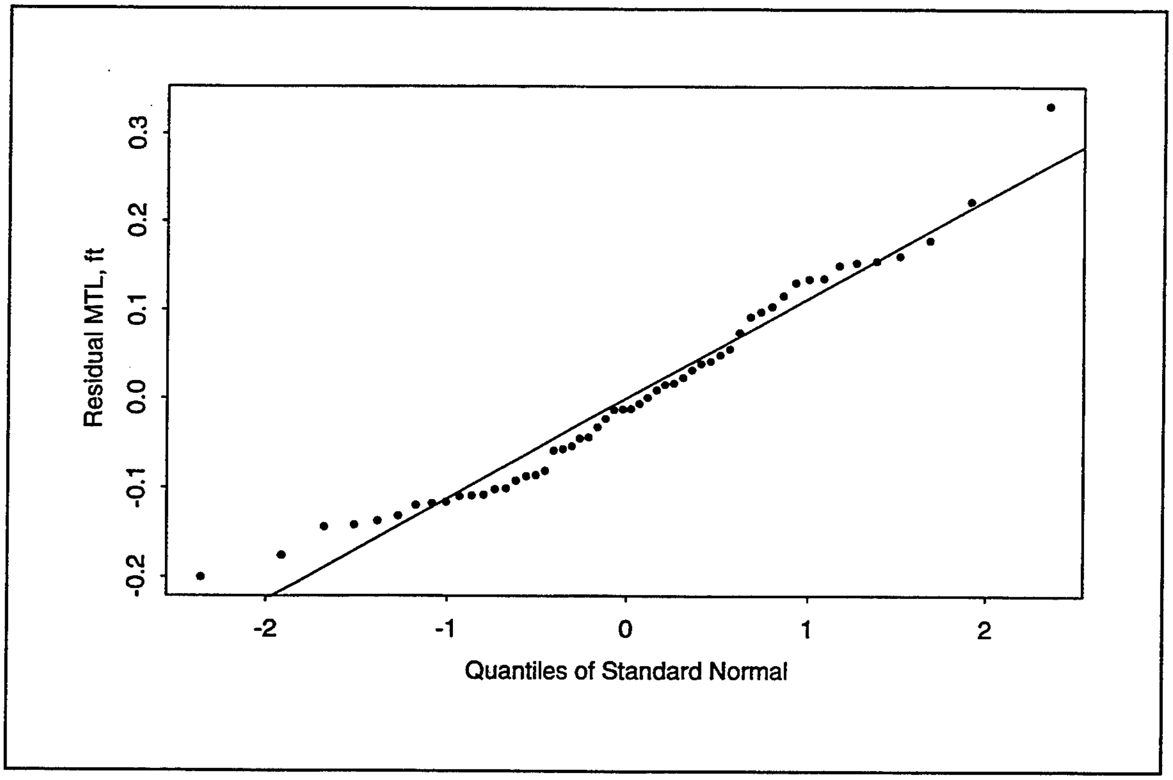

Figure 25. Probability plot for Fort Pulaski residuals (dots) and standard normal (line)

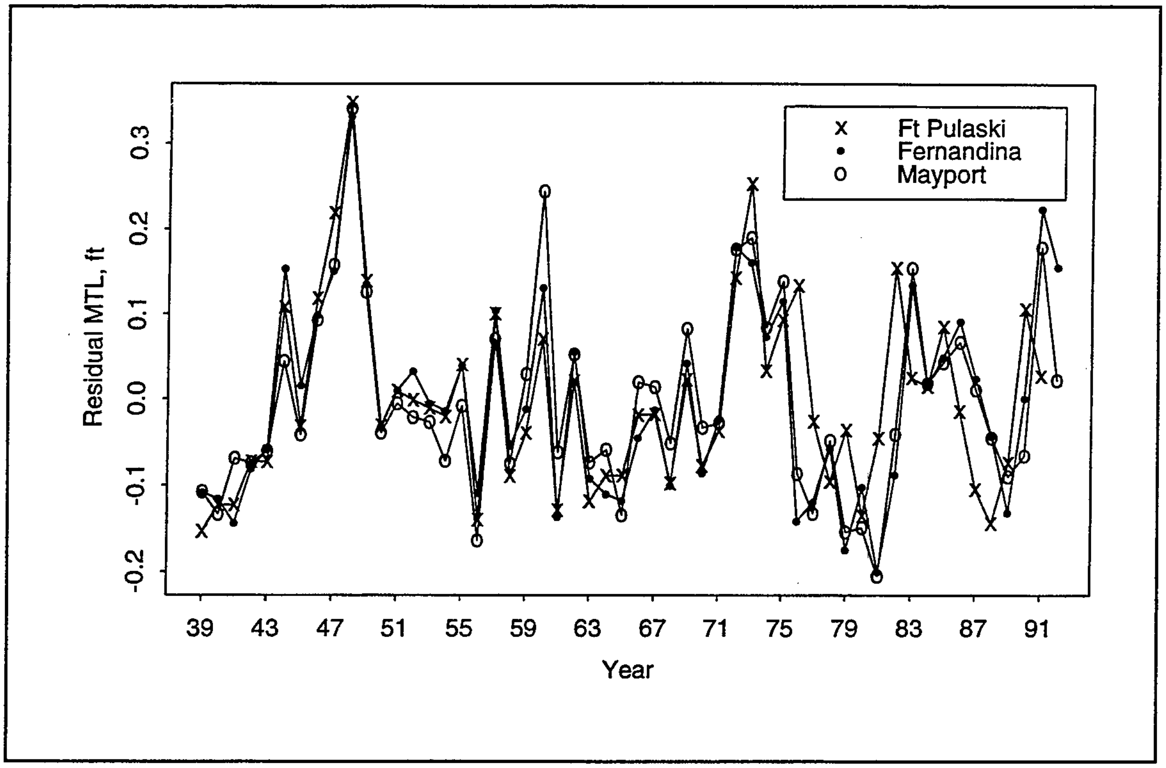

Figure 26. Probability plot for Fernandina residuals (dots) and standard normal (line)

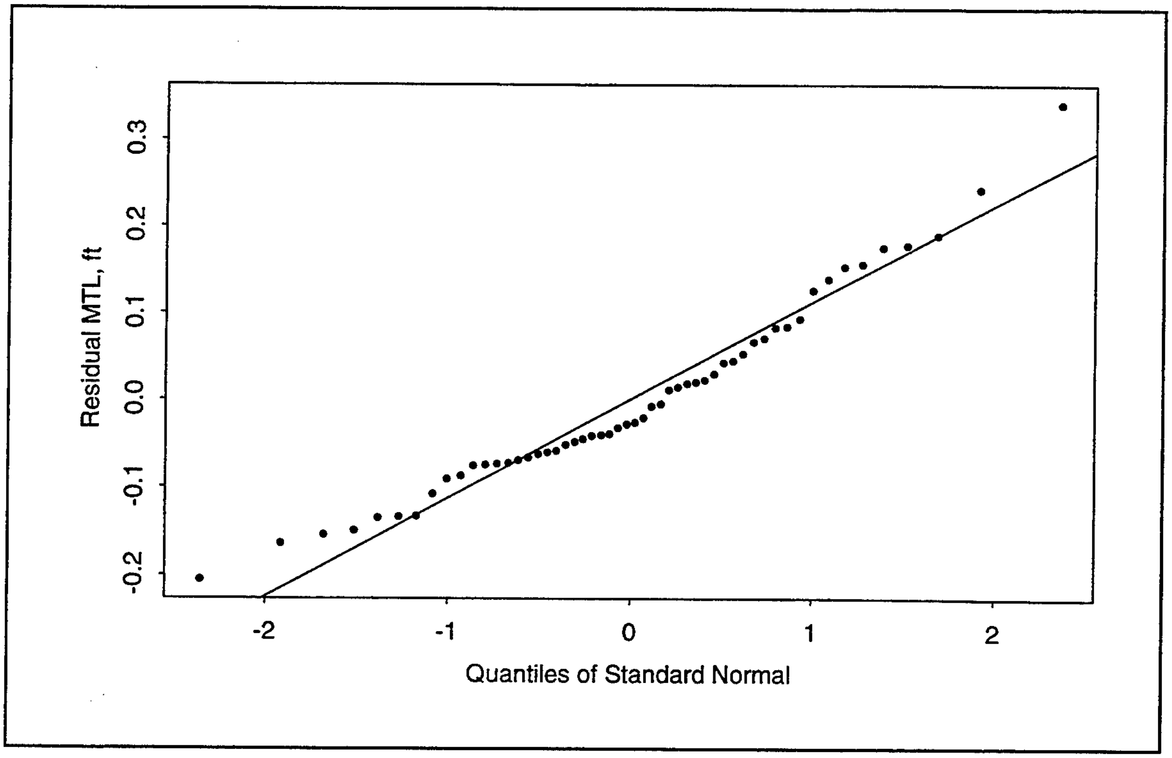

Figure 27. Probability plot for Mayport residuals (dots) and standard normal (line)

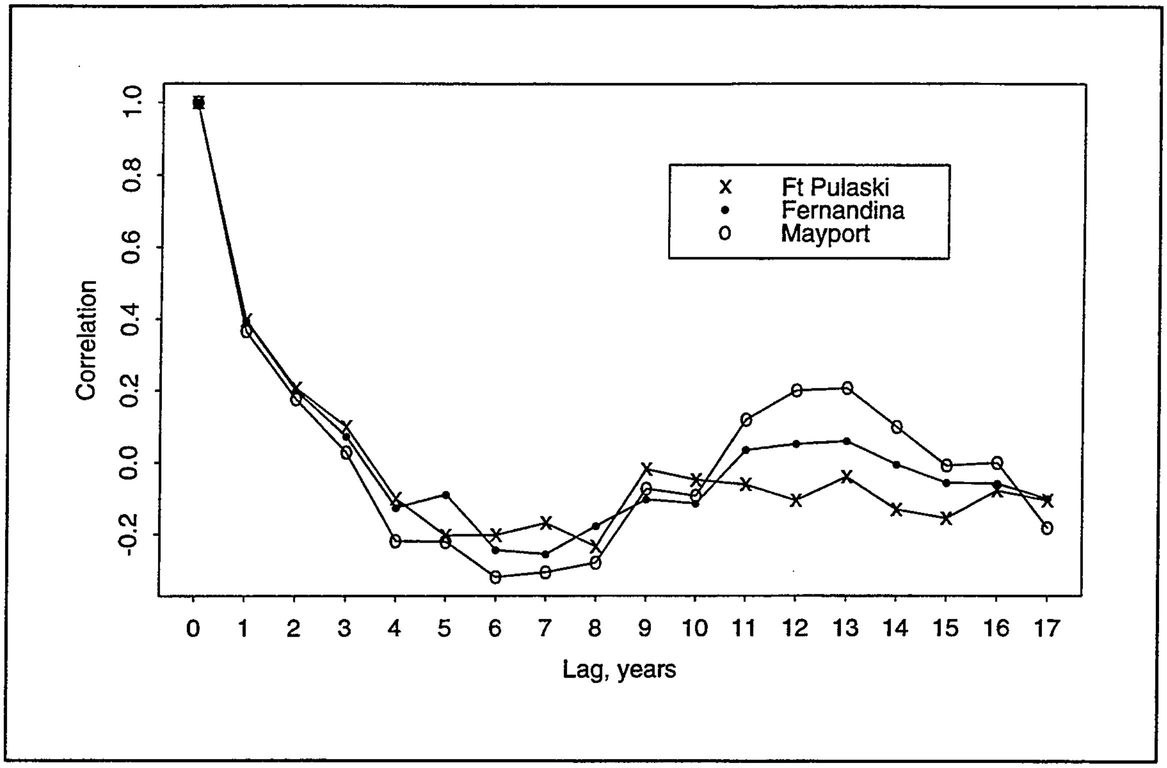

Figure 28. Correlation coefficient as a function of time separation (lag) in years for all three stations

4 Conclusions

In this report, an analysis was made of the long-term water-level record at Fernandina Beach, Florida, to determine if dredging performed from 1986-1988 in Cumberland Sound and St. Marys Entrance changed the water level in Cumberland Sound. The analysis considered mtl, mean range of tide, and mhw. Regional trends in rsl were reviewed, and accuracy of the water-level measurement was estimated. Water-level data were entered into the computer for analysis directly from NOS data sheets and verified for correctness.

Analysis and interpretation considered general behavior of the tide record through time, comparisons with tide records at stations immediately to the north (Fort Pulaski (Savannah), Georgia) and to the south (Mayport, Florida), and comparisons of tide level before and after dredging. A statical hypothesis test valid for correlated data was applied as an objective criterion for determining if the water level had changed by dredging.

Following are the major conclusions of this study:

a. The statistical hypothesis test indicated that there was no discernible change in mtl after dredging (after the long-term trend in water level is removed) to a 99-percent level of confidence. Sensitivity analysis indicated that a change in mean mtl for the post-dredging time period of about 0.15 ft would be required to be detected in the test. Measurement accuracy is estimated to be ±0.05 ft, and so resolution of the test is close to a physically meaningful interval of change.

b. For the period 1939-1992, mtl increased in Cumberland Sound at an annual rate of 2.4 mm/year. For comparison, mtl rose 3.0 mm/year at Fort Pulaski and 2.3 mm/year at Mayport (see Figures 5, 7, and 8).

c. The mtl tracked closely among the three tide stations (Figure 9). Notable short-term increases in mtl occurred at the stations from 1945-1948 (the most abrupt increase in the record), 1956-1957, 1970-1972, 1981-1983, and 1989-1991. The increase over 1989-1991, which might be attributed to dredging, occurred at Fort Pulaski and Mayport as well, and thus cannot be attributed solely to the subject dredging. Also, mtl in 1989 was at a local minimum, and the increase started 1 year after, or 2 years after major new-work dredging had ended (Tables 1 and 2). It is not

considered possible for a 2-year lag in influence to occur; in fact, water level would adjust continually during the 3-year period of dredging to reflect the changing bottom condition.

d. Tide range in Cumberland Sound has a periodicity of about 19 years (Figure 14). From 1992 to 1993 the range should cross through its long-term mean value and increase for the next several years.

e. The mhw (Figure 15) gradually increased form 1939-1992, and this tide datum tracked well in long-term trend and short-term variations for the three tide stations. During 1986-1989, which covers the period of dredging, mhw decreased uniformly at the three tide stations, then rose at the three stations in 1990, subsequently decreasing in 1992.

In summary, analysis has shown that dredging from 1986-1988 did not change the water level in Cumberland Sound.

References

American Society of Civil Engineers Task Committee. (1992). "Effects of sea-level rise on bays and estuaries," *Journal of Hydraulic Engineering* 118(1), 1-10.

Borgman, L. E. (1991). "FORTRAN software for the correlated, two-sample, Student's *t*-test," Statistics Laboratory Report No. 91-3, University of Wyoming, Laramie, WY.

Coast and Geodetic Survey. (1965). "Manual of tide observations," Publication 30-1, a revision of Special Publication No. 196, U.S. Department of Commerce, U.S. Government Printing Office, Washington, DC.

Cofer-Shabica, S. V., e. (1991). *Biological and physical aspects of dredging, Kings Bay, Georgia.* Series volume of *Coastlines of the World, Proceedings of Coastal Zone '91.* American Society of Civil Engineers, New York.

Edwing, R. F. (1991). "Next generation water level measurement system (NGWLMS) site design, preparation, and installation manual," National Oceanic and Atmospheric Administration, National Ocean Service, Rockville, MD.

Emery, K. O., and Aubrey, D. G. (1991). *Sea levels, land levels, and tide gauges.* Springer-Verlag, New York.

Fagerberg, T. L., Coleman, C. J., and Parman, J. W. (1991a). "Cumberland Sound monitoring; Report 1, 1988 data collection report," Technical Report HL-91-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

__________. (1991b). "Cumberland Sound monitoring; Report 1, 1989 data collection report," Technical Report HL-91-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Fisackerly, G. M., Fagerburg, T. L., and Knowles, S. C. (1991). "Estuarine dynamics at Cumberland Sound, Georgia, USA." *Biological and physical aspects of dredging, Kings Bay, Georgia.* S. V. Cofer-Shabica, ed., American Society of Civil Engineers, New York, 143-56.

Granat, M. A. (1990). "Numerical model predictions of Cumberland Sound sediment redistribution associated with Trident channel expansion," Miscellaneous Paper HL-90-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Granat, M. A., and Brogden, N. J. (1990). "Cumberland Sound and Kings Bay pre-Trident and basic Trident channel hydrodynamic and sediment transport hybrid modeling; Volume I, Main Text and Appendixes A, C, and D" Technical Report HL-90-21, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Granat, M. A., Brogden, N. J., Cartwright, J. T., and McAnally, W. H., Jr. (1989). "Verification of the hydrodynamic and sediment transport hybrid modeling system for Cumberland Sound and Kings Bay navigation channel, Georgia," Technical Report HL-89-14, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hicks, S. D. (1978). " An average geopotential sea level series for the United States," *Journal of Geophysical Research* 83(C3), 1377-79.

__________. (1989). "Tide and current glossary," National Oceanic and Atmospheric Administration, National Ocean Service, Rockville, MD.

Hicks, S. D., Debaugh, H. A., Jr., and Hickman, L. E., Jr. (1983). Sea level variations for the United States, 1955-1980," National Oceanic and Atmospheric Adminstration, National Ocean Service, Rockville, MD.

Kraus, N. C., Gorman, L. T., and Pope, J., ed. (1994). "Kings Bay coastal and estuarine physical monitoring and evaluation program: Coastal studies; Volume I, Main text and Appendix A," Technical Report CERC-94-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kraus, N. C., Gorman, L. T., and Pope, J. (1995). "Kings Bay coastal and estuarine physical monitoring and evaluation program: Coastal studies; Volume II, Appendices B-G," Technical Report CERC-94-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lyles, S. D., Hickman, L. E., Jr., and Debaugh, H. A., Jr. (1988). *Sea level variations in the United States 1855-1986.* National Oceanic and Atmospheric Administration, National Ocean Service, Rockville, MD.

Mann, D. W., and Mehta, A. J. (1993). "Constricting influence of tidal inlets on the measurement of sea level rise in bays," *Journal of Coastal Research*, Special Issue No. 18, 185-94.

Marmer, H. A. (1951). "Tidal datum planes," Special Publication No. 135, U.S. Department of Commerce, Coast and Geodetic Survey, U.S. Government Printing Office, Washington, DC.

McAnally, W. H., Jr., and Granat, M. A. (1990). "Cumberland Sound and Kings Bay pre-Trident and basic Trident channel hydrodynamic and sediment transport hybrid modeling; Volume II, Appendix B," Technical Report HL-90-21, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

McAnally, W. H., Jr., Letter, J. V., Jr., and Fagerburg, T. L. (1993). "Cumberland Sound Salinity Analysis," draft technical report, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Miller, I., and Freund, J. E. (1985). *Probability and statistics for engineers.* Prentice-Hall, Englewood Cliffs, NJ.

National Oceanic and Atmospheric Administration. (1985). "Index of tide stations United States of America and miscellaneous other locations," National Ocean Service, Rockville, MD.

National Research Council. (1987). *Responding to changes in sea level: Engineering implications.* National Academy Press, Washington, DC.

Pope, J., and Richardson, T. W. (1994). "Introduction," *Kings Bay coastal and estuarine physical monitoring and evaluation program: Coastal studies; Volume I, Main text and Appendix A,* N. C. Kraus, L. T. Gorman, and J. Pope, ed., U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Smith, J. B., Pope, J., Gorman, L. T., Martin, T., and Brinson, S. (1995). "Appendix C, Dredging and shoaling data," *Kings Bay coastal and estuarine physical monitoring and evaluation program: Coastal studies; Volume II, Appendices B-C,* N. C. Kraus, L. T. Gorman, and J. Pope, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Swanson, R. L. (1974). "Variability of tidal datums and accuracy in determining datums from short series of observations," NOAA Technical Report NOS 64, National Oceanic and Atmospheric Administration, National Ocean Service, U.S. Government Printing Office, Washington, DC.

Vemulakonda, S. R., and Scheffner, N. W. (1987). "Application of CIP modeling system to St. Marys Inlet, Florida." *Proceedings Coastal Sediments '87.* American Society of Civil Engineers, New York, 616-31.

__________. (1988). "Kings Bay coastal processes numerical model," Technical Report CERC-88-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Appendix A
Correlated Student's *t*-tests on Mean Tidal Levels

This appendix presents the calculation results of correlated Student's *t*-tests on mean tidal levels from Fernandina, Fort Pulaski, and Mayport. Notation appearing in the computer output is:

Ho: Null hypothesis
Ha: Alternative hypothesis
Alpha: Probability of rejecting the null hypothesis when it is really true
TCRIT: Value of *t*-statistic at which null hypothesis is rejected
T: Calculated *t*-statistic

Correlated Student's *t*-test, Fernandina

Ho: mean values of pre-1986 and post-1986 MTL are the same
Ha: mean values are different
IDECIDE = 1; ACCEPT Ho AND REJECT Ha
DEG. FREE., ALPHA = 52 .01000
TWO-SIDED TEST
TCRIT, T = 3.36937 -1.05914

Correlated Student's *t*-test, Fort Pulaski

Ho: mean values of pre-1986 and post-1986 MTL are the same
Ha: mean values are different
IDECIDE = 1; ACCEPT Ho AND REJECT Ha
DEG. FREE., ALPHA = 51 .01000
TWO-SIDED TEST
TCRIT, T = 3.36433 -.06254

Correlated Student's *t*-test, Mayport

Ho: mean values for pre-1986 and post-1986 data are the same
Ha: mean values are different
IDECIDE = 1; ACCEPT Ho AND REJECT Ha
DEG. FREE., ALPHA = 52 .01000
TWO-SIDED TEST
TCRIT, T = 3.39317 -.35139

Appendix B
Sensitivity Analysis on the Correlated Student's *t*-test

This appendix presents calculation results of a sensitivity analysis on the correlated Student's *t*-test with shifts in average mean tidal level for post-1986 data at Fernandina, Fort Pulaski, and Mayport.

Fernandina data with 0.15 ft added to post-1986 mean

Ho: mean values of pre-1986 and post 1986-MTL are the same
Ha: mean values are different
IDECIDE = 2; REJECT Ho AND ACCEPT Ha
DEG. FREE., ALPHA = 52 .01000
TWO-SIDED TEST
TCRIT, T = 3.36937 -3.38569

Fort Pulaski data with 0.21 ft added to post-1986 mean

Ho: mean values of pre-1986 and post-1986 MTL are the same
Ha: mean values are different
IDECIDE = 2; REJECT Ho AND ACCEPT Ha
DEG. FREE., ALPHA = 51 .01000
TWO-SIDED TEST
TCRIT, T = 3.36433 -3.52440

Mayport data with 0.18 ft added to post-1986 mean

Ho: mean values for pre-dredging and post-dredging data are the same
Ha: mean values are different
IDECIDE = 2; REJECT Ho AND ACCEPT Ha
DEG. FREE., ALPHA = 52 .01000
TWO-SIDED TEST
TCRIT, T = 3.39317 -3.42739

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13. ABSTRACT *(Maximum 200 words)*

Cumberland Sound, Georgia, is a large and complex estuary covering an area of approximately 240 square miles, which is connected to the Atlantic Ocean through a dredged inlet channel called St. Marys Entrance. St. Marys Entrance consists of a Federally maintained navigation channel protected by two jetties separating Cumberland Island, Georgia, to the north and Amelia Island, Florida, to the south. The channel through St. Marys Entrance is maintained at a 50-ft depth through significant dredging that occurred from 1986-1988. Questions arose as to whether this dredging had raised the water level in Cumberland Sound. The U.S. Army Engineer Waterways Experiment Station commissioned the study that is documented in this report in order to review and interpret the water-level record available from tide stations operated in Cumberland Sound by the National Ocean Service, National Oceanic and Atmospheric Administration. Objectives of this study were to analyze long-term water-level records to determine if recent (1986-1988) dredging along Cumberland Sound and St. Marys entrance altered the water level in Cumberland Sound and to quantify the change, if it was found.

Conclusions of the study were as follows:

a. A statistical hypothesis test indicated that there was no discernible change in mean tide level (mtl) after dredging.

b. For the period 1939-1992, mtl increased in Cumberland Sound at an annual rate of 2.4 mm/year.

(Continued)

14. SUBJECT TERMS

Cumberland Sound, Georgia	Mean tide level
Mean high water	St. Marys Entrance

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c. The mtl tracked closely among the three tide stations that were monitored.

d. Tide range in Cumberland Sound has a periodicity of about 19 years, and from 1992 to 1993, the range should cross through its long-term mean value and increase for the next several years.

e. Mean high water gradually increased from 1939-1992, and this tide datum tracked well in long-term trend and short-term variations for the three tide stations.